HEAT TRANSFER VARIABLES AFFECTING PROCESS DETERMINATIONS IN CONDUCTION HEATING INSTITUTIONAL SIZE RETORT POUCHES

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KEY TO SYMBOLS

A	Half slab thickness
a	Half slab width
B	Thermal process time. Total time at processing temperature.
b	Half slab length
Bi	Biot number = $h*A/k$
$(Bi)_{inc}$	Incremental Biot number = $h*\Delta x/k$
c	Height of air at slab center
D	Time at any temperature to destroy 90% of a microorganism
F	Equivalent minutes at a reference temperature, with respect to destruction of microrganisms.
f	Time for straight line portion of heating or cooling curve plotted on semi-log graph paper to transverse 1 log cycle.
g	Difference between T_{rh} and temperature of the food at the container coldspot at the start of cooling.
h	Surface heat transfer coefficient
j	Lag factor for heating or cooling curve
k	Thermal conductivity
M	$(\alpha*\Delta t)/(\Delta x)^2$
Pos	Relative position in slab = (inches from center)/A
Re	Reynolds number
t	Time
T	Temperature
V	Volume of air present

x	Position on width axis $(-a \leq x \leq a)$
y	Position on length axis $(-b \leq y \leq b)$
z	Height of air over any point (x,y) on slab surface $(0 \leq z \leq c)$
Z	Number of degrees Fahrenheit required to reduce the D-value by 90%
α	Thermal diffusivity
Δt	Time increment
Δx	Distance increment

Subscripts

c	Cooling
cd	Come down
cu	Come up
h	Heating
i	Initial
m	Heating medium
pi	Pseudo initial temperature for heating or cooling. Intersection of the straight line of a heating or cooling curve with zero time.
r	Retort
s	Surface
0	Current position in numerical equations
1	Position one increment closer to the center of the slab than the current position.
-1	Position one increment closer to the surface of the slab than the current position.

Superscripts

0	Time one increment previous to current time in numerical equations.
1	Current time in numerical equations

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Major Department: Food Science and Human Nutrition

One and 1.5 inch polycarbonate slabs were used to determine the resistances of components in an institutional sized retort pouch system to heat transfer. The components evaluated were 1) pouch material, 2) rack design, 3) flow rate of processing medium, and 4) entrapped air. Pouch material and perforated rack designs offered no significant resistance to heat transfer. A solid rack design resulted in variable results and reduced heat transfer rate. The solid rack design reduced heating rates more than cooling rates. Entrapped air in pouches greatly reduced heating rates and caused an upward migration of the cold spot.

Four different types of thermocouples and three different grounding methods were evaluated to determine the most consistent and accurate temperature response in heat penetration tests of pouches in pressurized water and steam-air retorts. Criteria for evaluating the response were the residual sum of squares from non-linear regression analysis and f_h and f_c values derived from the heat penetration data. Temperature measurement errors were found using both types of heating media for certain thermocouple types and grounding methods, while cooling data were found to be acceptable for most combinations. The best response was found with a thermocouple shielded with a stainless steel tube in which the measuring junction was electrically isolated from the tube.

The effect on process time of the positioning of the temperature measuring device in institutional size retort pouches was examined for low acid pouched foods . Numerical techniques were used to predict process time by the improved general method at various positions in an infinite slab. Regression models were developed for the prediction of process time and were used to identify the factors which significantly interacted with position of the temperature measuring device. Positioning was not critical within a small range near the center of the slab. A positioning accuracy of ±1/8 inch around the center of pouches having a thickness of greater than 0.5 inch did not significantly change the determined process time. This range increased as slab thickness increased.

CHAPTER I
INTRODUCTION

Thermal stabilization of food to produce a shelf stable product was first accomplished in the late 1700's by Nicolas Appert. Through the years a great deal of experience and research have resulted in the canned food supply of today. Due to this experience and research, the procedures for producing a shelf stable, commercially sterile canned food product have been well established. Retort pouches are a relatively new form of packaging. Initial experimental work was completed in the 1950's. Much of the data base and concepts used in producing and processing canned food can be applied directly to retort pouches; however, there are many retort pouch processing parameters which differ from those of cans. These must be identified and controlled to insure the consistent production of a commercially sterile, safe pouched food.

One of the major advantages of retort pouches over cans is that the thin heating profile of the retort pouch requires a shorter process time and thus the quality of a pouched product can be much higher than that of a comparable canned food product.

To take advantage of the thin profile and reduced process times, the retort pouch processor must avoid overprocessing. To avoid overprocessing and at the same time insure a safe product for the consumer, the variables associated with thermal processing must be known and controlled. Unfortunately, the thermal processing variables associated with processing pouches are greater in number and more critical than those associated with can processing.

The purpose of this research was to examine variables associated with the processing of institutional size retort pouches and to identify those having the greatest effect on the process time required to produce a commercially sterile pouched food product.

The research was conducted in three phases:

1) Heat transfer resistances encountered from the heating medium to the surface of the food in the pouch.
2) Temperature measurement errors associated with retort pouches.
3) Temperature sensor placement errors during heat penetration trials in retort pouches.

CHAPTER II
LITERATURE REVIEW

The retort pouch is a flexible food package designed to withstand the temperatures associated with commercial sterilization of food products. Initial investigations of the potential for flexible films for commercial sterilization of food was conducted by Hu et al. (1955). Results of this study indicated flexible films were available that would withstand the usual sterilization temperature of 250 F used for low-acid foods. Since this initial investigation, considerable research has been conducted to obtain a viable package which would meet the strength, integrity, and safety requirements needed for a shelf-stable, commercially sterilized food product. The result of this research was the current retort pouch material which usually consists of a 3-ply laminate of polyester for strength, aluminum foil for barrier properties, and a polyolefin for heat sealability. The development of the retort pouch was a joint effort involving both the government and private industry, most notably U.S. Army Natick R & D Command, The Continental Group, Inc., and Reynolds Metal Co. (Mermelstein, 1978).

According to Mermelstein (1978), there are a number of advantages which retort pouches have over cans and glass jars.

1. The retort pouch has a thinner profile, therefore it requires less processing time and there is less peripheral overprocessing.
2. The final pouched, processed product can be reheated rapidly by placing the pouch in boiling water.
3. The retort pouch can be easily opened using scissors or by tearing the top off.
4. The weight of retort pouch material is less than that of a comparable number of cans or glass jars.
5. Less storage space is required for the retort pouch material.
6. Less energy is required to manufacture retort pouch material.

The thin profile of the pouch compared to cans may result in shorter process times. Numerous investigations have compared the quality of products processed in retort pouches and cans. Sensory properties of foods packed in retort pouches have been found to be equal or superior to the same foods packed in cans of comparable or smaller net weight. This quality advantage has been described for fruits and vegetables (Thorpe and Atherton, 1972; Gould et al., 1962); cream style corn (Tung et al., 1975; Gould et al., 1962); chicken (Lyon and Klose, 1981); and various seafood products (Adams et al., 1983; Chia et al., 1983). Nutrient retention in pouches has also attracted interest. Castillo et al. (1980) used a rectangular parallelepiped model to predict nutrient retention in a conduction heating food. Abou-Fadel and Miller (1983) found green beans and cherries packed in retort pouches retained a greater percent of both thiamin and ascorbic acid than the comparable canned products. Retort pouched sweet potato puree exhibited enhanced retention of thiamin and riboflavin when compared to cans of equal volume (Rizvi, 1981).

Williams et al. (1982) stated that retort pouches had a significant advantage over cans when transportation costs were considered. This advantage was the result of the lighter weight of the empty retort pouch and reduced syrup/brine requirements of retort pouched fruits and vegetables. Steffe et al. (1980) found the total energy requirements for the production of retort pouch material and wholesale distribution to be 14% less than that required for a similar canning operation. Although retort pouches may require less processing time than comparable cans, this factor did not play a significant role in the overall cost comparison between retort pouches and cans (Williams et al., 1983). A retort pouch line compared very favorably to a canning line when operating costs were considered; however, the large initial capital expenditure could offset these advantages (Williams et al., 1983).

In addition to retail size retort pouches which contain approximately 8 ounces of product, there may be a viable market for institutional size retort pouches (Whelan and Whitehead, 1980). Morris (1981) predicted that the institutional size retort pouch would show the most rapid growth in the retort pouch market. Institutional size retort pouches usually contain approximately 5 lbs, although the actual size of the pouch depends on the product. In many cases institutional size retort pouches are in direct competition with the No. 10 can (Badenhop and Milleville, 1980). The pouches can be as large as 12 by 18 inches and are usually 0.75 to 1.5 inches thick (Milleville, 1980a). The institutional size retort pouch market may be easier to break into than the retail size retort pouch market due to a number of factors. The filling speed of No. 10 cans is much slower than smaller cans, thus the discrepancy between the filling of No. 10 cans and the institutional size retort pouch is not as great as it is for the retail size pouch. Also, user education on use and storage of the institutional size retort pouch would be less than that required for the retail size retort pouch (Mermelstein, 1976).

Heat Penetration Tests for Retort Pouches

Conducting a heat penetration trial with retort pouches is essentially identical to the procedure used for cans. There are a number of excellent discussions on the subject of heat penetration tests for cans (Ball and Olson, 1957; Stumbo, 1973; Pflug, 1975; Alstrand and Ecklund, 1952); therefore, the details of the actual procedure will not be discussed here. Even though the basic procedure for conducting heat penetration tests is the same for retort pouches, there are a few areas that present difficulties not experienced when dealing with cans. The major difficulties are experienced in temperature measurement, introduction of the temperature measuring device into the retort pouch, and location of the temperature measuring device at the cold spot of the retort pouch.

Thermocouple Errors

Davis et al. (1972) noted thermocouple measurement errors during thermal processing of retort pouches that were not experienced during processing of cans or glass jars. Errors as large as ±20 F were found when thermocouple data were compared to the retort mercury thermometer temperatures. Pflug (1975) also discussed temperature measurement errors during heat penetration tests with retort pouches. Pflug (1975) attributed these errors to the ability of the retort pouch to produce stray electrmotive forces (emf) in a water or steam environment above 140 F. Both Davis et al. (1972) and Pflug (1975) alleviated temperature measurement problems by using enamel-coated thermocouple wire and by grounding the measuring junction to the case of the recording potentiometer.

Peterson and Adams (1983) successfully used a different grounding method. The stainless steel sheath of a thermocouple was grounded to the frame of the retort during processing. This method was accomplished inside the retort and did not require a ground wire to be extended outside of the retort. The thermocouple used was sheathed in a stainless steel tube, but the tube was not a true electrical shield since the measuring junction of the thermocouple was in electrical contact with the tube.

Introduction of Temperature Measuring Device into the Retort Pouch

Introduction of the temperature measuring device into the retort pouch is more difficult than it is in the can due to the flexible nature of the pouch material. The use of the stuffing box or packing gland appears to be the most popular method of inserting the temperature sensor into a retort pouch (Berry and Kohnhorst, 1983; Peterson and Adams, 1983; Spinak and Wiley, 1982; Castillo et al., 1980; Tung et al., 1975; Davis et al., 1972; Turtle and Alderson, 1971; Goldfarb, 1970; Pflug et al., 1963). Generally, stuffing boxes obtain a hermetic seal by compression of rubber gaskets at the opening into the pouch and around the thermocouple wire or sheath. A hermetic seal is not guaranteed when a stuffing box is used, since the rubber gaskets must be tight enough to insure a seal. Overtightening can create problems by breaking small gauge thermocouple wires. Another problem occurs when multiple wires enter the same stuffing box: a hermetic seal is difficult to obtain in this situation.

Stuffing boxes are commonly made of metal or nylon. A metal stuffing box can affect heat penetration due to the heat sink effect. Care must be taken to insure the stuffing box is far enough away from the temperature measuring device to avoid this effect. Spinak and Wiley (1982) determined that a distance of 1.5 inches between a brass stuffing box and the measuring junction of a thermocouple was adequate to insure a negligible effect on heat penetration data.

The caulk method of introducing the temperature measuring device into a pouch involves introducing thermocouple wire through a small hole in the pouch material and sealing the hole with silicon caulk (Roop and Nelson, 1982; Spinak and Wiley, 1982) or adhesive (Thorpe and Atherton, 1972). There are a number of disadvantages to this method. First, a large amount of time is required for the caulk to cure. Second, to obtain a hermetic seal the caulk must adhere very well to both the pouch material and the thermocouple wire entering the pouch. If the thermocouple wire used is insulated with teflon, adherence is very difficult to obtain.

Wornick et al. (1960) used a method similar to the caulk method. A small slit was made in one of the pouch edges, thermocouple wire was inserted through the slit, then the slit was sealed by means of two rubber gaskets and a screw clamp.

Pflug et al. (1963) introduced thermocouple wires into the pouch through the pouch seal. Insulation was stripped off the thermocouple wires where they were to be incorporated into the seal, then the wires were cleaned and coated with 3 to 5 layers of a lacquer that would heat seal with the pouch material. With 30 gauge wire it was necessary to separate the thermocouple wires by at least 0.25 inch to avoid bridging of the pouch seal across the two wires.

Placement of the Temperature Sensing Device

To obtain valid heat penetration data for establishing a process for a thermally stabilized low acid food product, the temperature sensing device must be located in the slowest heating point of the container. This is difficult when dealing with retort pouches due to the flexible nature of the pouch (Milleville and Badenhop, 1980). A number of methods have been developed to deal with this problem.

When a pouch contains large particulates, slices of meat, fish fillets, etc., the measuring junction of the thermocouple is commonly embedded in a particle or placed between slices of the food (Adams et al., 1983; Spinak and Wiley, 1982; Berry, 1979; Pflug, 1975; Thorpe and Atherton, 1972; Turtle and Alderson, 1971; Pflug et al., 1963). With these products one can expect greater variation in heat penetration data than with homogeneous products due to the natural variation found in particle size and thickness of food slices.

The spacer block or spacer disk method uses blocks or disks corresponding to the desired thickness of the retort pouch. The blocks or disks have a center hole through which the thermocouple is inserted and therefore the block or disk acts as a support to maintain the desired thermocouple position (Adams et al., 1983; Peterson and Adams, 1983; Milleville and Badenhop, 1980; Thorpe and Atherton, 1972). The disks or blocks may be made of any material which will maintain its integrity at processing temperatures.

This method works well for confined pouches. Problems may be encountered with unconfined pouches or pouches containing entrapped air due to expansion of the pouch during processing. The thermocouple remains where it was originally placed; therefore, any movement of the cold spot due to pouch expansion is not adjusted for.

If wire thermocouples are used with the spacer block method, the disks or blocks must be wide enough to minimize the possibility of their tipping over and thus changing the position of temperature measurement. This problem is minimized if rigid thermocouples are used.

The blocks or disks should be situated far enough away from the measuring junction of the thermocouple to insure that the block or disk does not affect the heat penetration data (Milleville and Badenhop, 1980).

The spring method for positioning the temperature measuring device inside a retort pouch uses a wire spring of the same wound diameter as the desired thickness of the retort pouch. The thermocouple wire is clamped to the ends of the spring and the measuring junction is doubled back and positioned in the center of the spring (Tung et al., 1975; Pflug, 1975; Davis et al., 1972). Obviously, this method was designed for wire thermocouples and would not be applicable to rigid thermocouples. As in the spacer block method, the thermocouple position is constant and any expansion of the pouch during processing is not accounted for in thermocouple position.

The self-centering strip method consists of a strip of retort pouch material which is folded into the shape of a "V" with tabs on both ends. The tabs are heat sealed to the top and bottom of the inside of the pouch and the thermocouple is placed through the apex of the "V". The "V" of pouch material is somewhat fragile; therefore, to avoid deformation this method should be used only with fairly large gauge wire thermocouples and liquid type products (Berry and Kohnhorst, 1983; Roop and Nelson, 1982; Spinak and Wiley, 1982; Thorpe and Atherton, 1972; Turtle and Alderson, 1971; Pflug et al., 1963). The advantage of this self-centering method is the ability to maintain the thermocouple at the center of the pouch when expansion of the contents occurs during processing.

The "H" method (Nioras, 1982) uses a polypropylene support in the shape of an "H" which fits inside a retort pouch. The crossbar of the "H" is used to maintain the thermocouple at the desired location. One disadvantage of the "H" method is that a different support would be needed for any change in pouch dimensions.

Modeling the Retort Pouch

Often it is desirable to model a process to predict process time or retention of some quality factor during processing. An appropriate model can also be used to aid in computer control of a thermal process (Teixeira and Manson, 1981). Thermal processes for canned or retort pouched food can be modeled by two methods. The heat conduction equation for the appropriate geometry can be solved for various conditions (Carslaw and Jaeger, 1959) and used for the prediction of time temperature relationships. The alternate method is to use numerical techniques. The use of numerical techniques results in more flexibility than the use of the exact solution of the heat conduction equation, since changes in the boundary conditions during processing, such as those found during a process deviation, are easily handled.

A number of numerical techniques are available which can be used to model a thermal process. Only three of these techniques will be discussed here. The most popular numerical method used for modeling thermal processes for canned or pouched food products is the explicit forward direction finite difference method. This method consists of using a representation of the partial derivative heat conduction equation in a Taylor's series form, which results in the commonly used explicit forward direction finite difference mathematical model. The development of the finite difference equation is straightforward and can be found in a number of heat transfer or diffusion textbooks (Chapman, 1974; Crank, 1975; Holman, 1976). This explicit method calculates a temperature at a future time by using the present temperature of the point of interest and its surrounding points. Thus, a future temperature is calculated directly from temperatures that have already been calculated. One disadvantage of this explicit method is that it is not inherently stable. The choice of a distance increment limits the choice of time increments. As the distance increment is decreased, the time increment must also be decreased. This can cause a large increase in computation time as one decreases the distance increment. However, this disadvantage has been reduced with the availability of relatively inexpensive computer time.

Backward direction finite difference methods or implicit methods do not have the stability problems associated with the explicit method. The backward direction method is developed in a manner similar to that of the forward direction method. The backward difference method uses temperatures from a future time increment to predict the present time temperature. Therefore, each future time increment must be solved as a series of simultaneous equations. The advantage of the backward direction method is that it is unconditionally stable; thus, large time increments can be chosen for a small distance increment. This can result in a reduction of computation time when compared to the forward direction method.

Another numerical technique used for analysis of heat transfer problems is the finite element method. The major advantages of the finite element method are the relative ease with which it handles irregular shapes and complex boundary conditions (Burden et al., 1981). The finite element method has not been used widely for modeling of thermal processing of cans or retort pouches, probably because the shapes being dealt with are simple and the finite difference methods have no problem dealing with the boundary conditions normally found during thermal processing of food products.

Models for canned food employ either the exact solution of a finite cylinder or numerical techniques for the prediction of the temperature history of the food during the process. Hayakawa and Ball (1971) developed a theoretical method based on the exact mathematical solution of the conduction heating equation for predicting temperatures of food in a can for various retort temperature profiles. Teixeira et al. (1969a, 1969b) used a forward direction finite difference technique to predict spore survival and nutrient retention in canned conduction-heated food. Manson et al. (1974) developed a forward direction finite difference numerical model applicable to pear-shaped containers.

The retort pouch has been modeled as a rectangular parallelepiped or infinite slab. Manson et al. (1970) used a forward direction finite difference technique to model lethality and nutrient retention in rectangular containers. Ohlsson (1980) used an infinite slab model and a forward direction finite difference technique to optimize quality factor retention during thermal processing. Castillo et al. (1980) developed a model using the exact mathematical solution to the heat conduction equation for a parallelepiped geometry. This model was used to predict nutrient retention during processing.

The geometry of the retort pouch, especially the larger institutional size retort pouch, can usually be modeled as an infinite slab with only minor errors (Adams et al., 1983). However, as the thickness of the pouch increases in relation to the length and width, the rectangular parallelepiped geometry may become the correct model.

Thermal Processing Determinations

As defined by Title 21 of the Code of Federal Regulations, Part 113.3 (1983), a minimum thermal process is the application of heat to a food which will ensure the destruction of all microorganisms of public health significance. Commercial sterility accomplishes the minimal thermal process plus the destruction of microorganisms capable of growth at ambient temperatures encountered during storage and distribution of the food product. Commercial sterility does not imply that all microorganisms and spores have been destroyed. There are usually spores present in a commercially sterile food product, but these are spores of thermophilic microoganisms. These spores are very heat resistant and to destroy all of them would result in severe overprocessing of the food product. The spores remaining in a commercially sterile food product will not reproduce under normal storage conditions. If by temperature abuse the spores do grow, they will spoil the product but their growth will not result in a public health hazard.

The organism of greatest concern in thermal processing of low acid food is *Clostridium botulinum*. Since microorganisms are destroyed following first order kinetics, it is not possible to reduce the population of a microoganism to an absolute value of zero. Instead, the population of the microorganism is reduced to a level where the probability of any survivors is very small. The 12D concept establishes a process that will reduce the number of *C. botulinum* spores present to a probability of less than one surviving spore in 10^{12} containers (Stumbo, 1973). Thermal processes usually exceed this Botulinum cook for a safety factor and to reduce the numbers of other more heat resistant microorganisms which are capable of spoiling the food product.

There are a number of mathematical methods for determining a thermal process for a food product, which have been reviewed by Hayakawa (1978). Of the available methods, two have been used extensively. These are the improved general method and Ball's formula method.

The general method of process evaluation was first presented by Bigelow et al. (1920) and improved by Ball (1928) and Schultz and Olson (1940). The improved general method is also discussed in detail by Ball and Olson (1957), Stumbo (1973), and Hayakawa (1978). The improved general method is based on the fact that any temperature has a certain amount of sterilizing value and that sterilizing value can be converted into minutes at a reference temperature. The reference temperature commonly used in the food industry for low acid thermally processed foods is 250 F. The mathematical relationship used for calculating an F-value of a process is

$$F = \int_0^t 10^{(T-T_{ref})/Z} dt$$

where F is the equivalent number of minutes of processing at T_{ref}, t is the total time of the thermal process, T is the temperature at any given time, T_{ref} is the reference temperature (usually 250 F for low acid food products), and Z is the number of degrees Farhenheit required to change the D-value of a microorganism by a factor of 10. The D-value is the number of minutes at a specific temperature required to decrease the population of a given microorganism or spore by 90%. The F-value of a process is commonly termed F_o when the reference temperature is 250 F and the Z-value is 18 F.

The Ball formula method has been used extensively in the determination of thermal processes for food products. The method was introduced by Ball (1923) and subsequently examined and modified (Alstrand and Benjamin, 1949; Alstrand and Ecklund, 1952; Ball and Olson, 1957; Stumbo, 1973; Flambert and Deltour, 1977). The following discussion of the Ball formula method includes the modifications of Stumbo (1973).

The Ball formula method for process time calculations requires the measurement of a number of heat penetration parameters of the food. These include

f_h Time for the straight line portion of the heating curve to transverse one log cycle.

f_c Time for the straight line portion of the cooling curve to transverse one log cycle.

j_h A heating lag factor. Calculated as the ratio of the temperature differential of retort temperature and the temperature obtained by extension of the straight line portion of the heating curve to zero process time to the temperature differential of retort temperature and actual initial product temperature.

$j_h=(T_{rh}-T_{pih})/(T_{rh}-T_{ih})$

j_c A cooling lag factor. Calculated in a manner similar to j_h.

$j_c=(T_{rc}-T_{pic})/(T_{rc}-T_{ic})$

The basic formula used for process time calculations is

$$B = f_h \log(j_h(T_{rh}-T_{ih})/g)$$

where g is the difference between retort temperature and temperature of the food at the cold spot of the container at the start of cooling, and B is the heating time required for the process starting at the corrected zero time.

There exists a relationship between g, f_h, and the sterilization value received by the food product. Through this relationship it was possible to develop tables to predict g knowing f_h and the desired F_o value of the process. Jen et al. (1971) also included j_c in this relationship and developed tables including j_c. A listing of these tables can be found in Stumbo (1973).

A number of assumptions were made in the development of Ball's formula method. The original method assumed a constant j_c of 1.41. Stumbo (1973) included the effect of j_c in his modification of the Ball formula method. A second assumption is that f_h is equal to f_c.

The calculated process time or B-value as presented earlier represents a process time in which the retort temperature is achieved instantaneously. In reality there is often a finite come up time for the retort to reach processing temperature. In practice the come up time may be disregarded and zero process time is taken as the time when the retort reaches processing temperature (Tung and Garland, 1978). The come up time can contribute significantly to the lethality achieved during a process, especially if come up time is long. Ball (1923) found that 42% of the come up time could be included as time at the retort temperature. Townsend et al. (1949) found that this correction factor applied to processing jars and cans. Alstrand and Benjamin (1949) determined the correction factor to be close to 42% with a linear temperature rise; however, they found a correction factor of approximately 70% when retort come up followed a semi-logarithmic curve. Uno and Hayakawa (1980) used a dimensional analysis approach to predict come up time correction factors for conduction-heated foods. They found the shape of the retort come up temperature profile had a significant effect on the come up correction factor. Berry (1983) developed a method for determining the come up time correction factor. He also found that the 42% correction factor was adequate for linear come up time retort temperature profile but was too small for an assymptotic retort temperature profile.

Ball's formula method was developed for use on canned food. Spinak and Wiley (1982) evaluated the use of the Ball formula and the improved general methods for process evaluation of retort pouches. These authors found the Ball formula method to be a reliable method for process evaluation of retort pouches.

Critical Processing Factors for Retort Pouches

A critical processing factor is defined as "any property, characteristic, condition, aspect, or other parameter, variation of which may affect the scheduled process and the attainment of commercial sterility" (21 CFR 113, 1983). Examples of critical processing factors include headspace in cans, maximum fill weight, product consistency, etc. The critical processing factors for cans have been established through years of practical experience and research. Many critical processing factors for cans are directly applicable to retort pouches; however, due to the flexible nature of the retort pouch, there are a number of factors that are different from or additional to those established for cans. The following discussion will deal with some of the critical processing factors which are unique to retort pouches.

Food Product Type

During thermal processing it is advantageous to capitalize on convective heating in canned foods, whether natural or forced. Compared to conduction, convection increases heating rate and decreases process times. It would therefore be desirable to have convective heating in retort pouches. Terajima (1975) indicated that in retort pouches, the type of product, whether liquid or solid, may be more important in determination of total process time than the type of heating medium or its circulation rate. However, retort pouches do present some interesting problems. First, the thin profile of horizontally positioned pouches does not allow natural convection to occur as readily as in cans. Second, retort pouches typically do not contain an appreciable headspace which is necessary for mechanically aided convection. There is some question as to whether retort pouches should be rotated to enhance heat transfer rate. Some manufacturers feel that retort pouches should not be rotated under any conditions

(Beverly, 1980; Milleville and Badenhop, 1980) due to possible damage to the integrity of the pouch seals. However, others have found no problems with rotation and have found a reduction in process time required when pouches were rotated (Toska, 1982). It was not determined whether this decrease in process time was the result of an increase in the surface heat transfer coefficient or the result of forced convection. Roop et al. (1983) determined the effect of rotation on seal strength of retort pouches. They found that while rotation during processing did not adversely affect the seal strength after processing, the seal strength was reduced significantly during processing. This reduced seal strength during processing may be more significant when dealing with institutional size retort pouches due to the large quantity of product present (Abbott, 1982). Also, a liquid product packed in an institutional size retort pouch could experience excessive hydraulic forces during the physical abuse of distribution and thus not survive intact without additional case cushioning.

Entrapped Gas

It is generally recognized that it is desirable to remove excess air from retort pouches before the final seal is made. There are a number of methods available to accomplish this (Lopez, 1981). Retort pouches are usually vacuum sealed either by being placed into a vacuum chamber or by use of a snorkel type apparatus placed inside the pouch. Pouches can also be steam flushed with either saturated or superheated steam just prior to sealing. The steam takes the place of the headspace gas and condenses when cooled. It has been suggested that a maximum of 2% air by volume be allowed in a sealed retort pouch; however, some producers feel that this is an unreasonable figure and that more should be allowed (Milleville and Badenhop, 1980).

Entrapped air, or any noncondensible gas in a retort pouch can come from a number of sources. Pouches that are filled and sealed cold can contain a large amount of air dissolved in the product itself. The order of filling a pouch may allow air to be entrapped and not easily removed (Milleville and Badenhop, 1980). If vacuum sealing is not adequate, air can remain in the pouch after sealing. Air can also be entrapped in the tissue of the food being pouched. Unblanched meats were found to have more than 20 ml of air per 100 grams, and raw vegetables were found to have more than 10 ml of air per 100 grams at room temperature and pressure (Milleville and Badenhop, 1980). Beverly et al. (1980) reported up to 200 ml of occluded air in the amount of product to be put into an institutional size retort pouch. They also reported finding 60 to 80 ml of air in vacuum sealed institutional size retort pouches.

A number of methods are available for the measurement of entrapped gas in a retort pouch. The simplest of these is the destructive method in which the pouch is opened under water, the gas escaping from the pouch is collected in a inverted graduated cylinder and the volume is measured (Shappee and Werkowski, 1972). There are two nondestructive methods for the measurement of entrapped gas in a retort pouch. Shappee and Werkowski (1972) and Ghosh and Rizvi (1982) first weighed the pouch in water, then placed it in a chamber filled with water. Air was removed from the chamber until the pouch floated. The amount of entrapped air in the pouch was then calculated with an equation derived from Archimedes Principle and Boyle's Law. Gylys and Rizvi (1983) presented a nondestructive method for entrapped air measurement for polymeric packages that floated or did not float at atmospheric pressure. The method was based on the measurement of volume change of the package at two pressures. The amount of entrapped gas could then be calculated from an equation derived from Boyle's law.

The presence of entrapped gas in a retort pouch during processing has two major effects. First, as the temperature increases during processing the gas will expand, possibly to the point where the retort pouch seals are threatened due to excessive internal pressure. Second, the entrapped gas can significantly reduce the rate of heat transfer during processing.

A number of researchers have expressed concern over the expansion of entrapped gas during processing (Nelson and Steinberg, 1956; Davis et al., 1960; Gould et al., 1962; Whitaker, 1971, Davis et al., 1972; Milleville and Badenhop, 1980). The problem of gas expansion during processing can be minimized by the use of overriding air pressure in the retort vessel during processing. Whitaker (1971) derived an equation which would calculate the amount of overriding air pressure necessary to prevent excessive expansion and pressure increase inside a retort pouch. The use of overriding air pressure during processing of retort pouches is generally accepted and is considered a critical factor (Milleville and Badenhop, 1980).

The other problem presented by the presence of entrapped air in retort pouch processing is the possible reduction of heat transfer rate (Nelson and Steinberg, 1956; Milleville and Badenhop, 1980). Entrapped gas has the greatest effect on heat penetration when pouches are processed in the horizontal position. Retort pouches are generally processed horizontally (Milleville and Badenhop, 1980), while institutional size retort pouches are almost exclusively processed in the horizontal position because of the large amount of product present. Processing vertically could put undue stress on the pouch seals. Beverly et al. (1980) found that as the amount of entrapped gas increased, the required process time for an equivalent sterilization value also increased. The increase in process time was found to be greater with pouches that were allowed to expand freely. Huerta-Espinosa (1981) examined the effect of entrapped air on processing requirements of pears and green beans. Process times for both products were found to increase approximately 15% for each 100 ml of air in 12 by 15 by 1.5 inch retort pouches. Huerta-Espinosa (1981) also showed a movement of the cold spot upward in the presence of entrapped air; however, this effect was not quantified. Berry and Kohnhorst (1983) examined the effect of entrapped gas on processing of institutional size retort pouches. They also found an upward movement of the cold spot with increased air content. The sterilization value of a given process was found to decrease as the amount of entrapped gas increased; however no replicates of the tests performed on the two products were done.

Heating Media Used for Retort Pouch Processing

The ideal heating medium for processing retort pouches would be 100% steam, as is used for cans, due to its large surface heat transfer coefficient. Retort pouches cannot safely be processed in 100% steam for two reasons. First, the expansion of entrapped gas during processing could put excessive stress on the pouch seals as discussed earlier. Second, as the pouch contents approach retort temperature, a decrease in retort pressure below the operating pressure could cause a large internal pressure increase in the pouch and thus threaten the integrity of the pouch (Goldfarb, 1970). For these reasons retort pouches are processed in steam-air mixtures or in water with overriding air pressure.

The control of a water process is generally recognized as being less complicated than control of a steam-air process (Parcell, 1930a; Parcell, 1930b; Pflug and Borrero, 1967; Milleville, 1980c); however, there are a number of commercially available retorts successfully utilizing steam-air as the processing medium (Milleville, 1981).

During steam-air or water processing the main concerns are to maintain all parts of the retort at the processing temperature and to maintain a constant rate of heat transfer during processing (Milleville and Badenhop, 1980).

The maintenance of retort temperature during water processing is usually accomplished by recirculating the heating medium (Peterson and Adams, 1983; Davis et al., 1972; Pflug and Borrero, 1967) and/or by bubbling air through the retort vessel to increase mixing (Berry and Kohnhorst, 1983; Berry, 1979; Davis et al., 1972; Pflug and Borrero, 1967). The amount of agitation or the rate of flow of the processing water has a significant effect on the rate of heat transfer into the retort pouch. Berry and Kohnhorst (1983) demonstrated a large decrease in the sterilization value achieved when only natural convection was used instead of bubbling air through the retort vessel. This large decrease was no doubt the result of a reduced surface heat transfer coefficient. Pflug and Borrero (1967) observed a decrease in rate of heat transfer as the rate of processing water circulation decreased. They attributed this decrease to a decrease in the surface heat transfer coefficient. Peterson and Adams (1983) examined the effect of water velocity on heat transfer rates. Apparent surface heat transfer coefficients were calculated and ranged from 33 to 48 BTU/hr ft^2 F for Reynolds numbers of 3,000 to 33,000 respectively. Process times as calculated by the formula method (Stumbo, 1973) increased by 9.6% from the low to high flow rate.

When retort pouches are processed in steam-air, a positive flow of the heating media is required as it is in water processing (Milleville, 1980b; Pflug and Borrero, 1967). This requirement is more important than it is when processing in 100% steam due to the possibility of air pockets forming after condensation of the steam on the surface of the pouch.

Temperature control of a steam-air process is more difficult than temperature control of a water process, especially during the come up period when there is a large initial heat demand (Helmer et al., 1952; Parcell, 1930a). Pflug and Borrero (1967) suggested using 100% steam for the come up period, and introducing air after the processing temperature had been reached. This method gave improved control of temperature during the initial stages of the process.

Surface heat transfer coefficients of steam-air mixtures are known to be smaller than those of 100% steam (Sparrow and Lin, 1964). Pflug and Blaisdell (1961) found an increase in heat transfer rate with an increase in the velocity of the steam-air mixture. Adams et al. (1983) found apparent surface heat transfer coefficients near 50 BTU/hr ft^2 F for steam-air mixtures. The coefficients showed a trend to increase with an increase of flow rate of the steam-air mixture. Ramaswamy et al. (1983) presented a method for the determination of surface heat transfer coefficients of steam-air mixtures based on a lumped capacity method (Kreith, 1973). They reported coefficients much higher than those reported by Adams et al. (1983).

Another consideration in processing with steam-air mixtures is the percentage of steam to use during processing. Generally, little difference has been found in observed heat transfer rates of foods or food simulating materials with steam percentages from 75 to 100% (Adams et al., 1983; Yamano, 1976; Terajima, 1975; Pflug et al., 1963). Ramaswamy et al. (1983) used a more sensitive method and did find an increase in heat transfer rate and surface heat transfer coefficient with increasing steam percentage.

Heat Penetration Through Retort Pouch Material

The resistance to heat transfer of plastics compared to metal has been a concern in processing retort pouches. Nelson and Steinberg (1956) felt that the heat transfer resistance due to the plastic would be negligible; however, no evidence was presented in support of this statement. Wornick et al. (1960) tested the resistances of films up to 0.003 inch thick by evaluating the time for pouches filled with water to reach the processing temperature of 212 F. They concluded that there was no significant effect on heat transfer due to changes in pouch thickness; however, they experienced a large amount of variation between replicate pouches which may have hidden any effect of the pouch material. Chapman and McKernan (1963) calculated the effect of high density polyethlyene of various thicknesses on thermal process times for dog food in a 4.75 by 3.75 by 1.5 inch container. When tinplate was used, the container required a process time of 49 minutes. When 0.008 inch polyethylene was used, 3 additional minutes were required for an equivalent process. Eight additional minutes were required for a container constructed of 0.020 inch polyethylene.

Racking Systems Used for Retort Pouches

The flexible nature of the retort pouch requires that it be supported in some manner during processing. Two types of support have been used, confined and unconfined. It is generally recommended that the confined method be used (Milleville and Badenhop, 1980). Confinement of a retort pouch maintains the pouch in a known geometry during processing, thus reducing the variation in geometry that would be experienced if the pouch was allowed to expand freely (Beverly et al., 1980). With a confined racking system, a process can be designed in the maximum thickness the pouch can obtain, thus insuring an adequate process (Beverly et al., 1980; Milleville and Badenhop, 1980; Berry, 1979; Davis et al., 1972; Pflug et al., 1963). Milleville and Badenhop (1980) also suggest that minimum pouch thickness may also be important in racking systems designed with solid plates. Pflug et al. (1963) calculated the resistance to heat transfer from 0.125 inch aluminum and 0.0625 inch steel to be negligible; however, if the top and bottom of the pouch are not in contact with the solid plates, reduced heat transfer may result.

The other critical factor in the design of the racking system is that there must be a channel for the heating medium on both sides of the rack (Beverly et al., 1980; Milleville and Badenhop, 1980; Berry, 1979; Davis et al., 1972; Pflug et al., 1963) and that the channels must allow for a uniform flow of the heating medium between all channels (Beverly, 1980; Milleville and Badenhop, 1980).

CHAPTER III
HEAT TRANSFER RESISTANCES OF RETORT POUCHES

Introduction

In designing a safe thermal process for low acid food packaged in a retort pouch, many factors, in addition to those normally considered for processing foods in cans must be considered. This is because of the construction of the retort pouch material and its flexible nature.

The pouch material itself, although very thin, is a poorer conductor of heat than the metal of a can. Nelson and Steinberg (1956) state that the pouch material should not affect heat penetration rate, but no data were presented to support this statement. Wornick et al. (1960) tested films up to 0.003 inch thick and found that film thickness did not change the heating time appreciably. However, variation in data from different pouches was great and could have hidden any subtle differences which may have existed. Chapman and McKernan (1963) conducted a study of the effect of thickness of plastic material on heat penetration. Their calculations showed that dog food processed in a 4.75 X 3.75 X 1.5 inch container constructed of 0.008 inch high density polyethylene required a process time of 52 minutes compared to 49 minutes required by a similar container constructed of tinplate.

The flexible nature of the retort pouch requires that it be supported during processing in order to maintain a known geometry. It has been established that channels for the heating medium between pouches are needed for proper heat transfer (Beverly et al., 1980). However, the material used to construct the racking system has not been examined critically. Pflug et al. (1963) used a racking system of solid 1/8 inch aluminum. They calculated the effect of the metal rack on heating rate to be negligible. However, it has been suggested that an underfilled retort pouch not in intimate contact with both plates of the racking system may heat more slowly than one that is in intimate contact with both plates (Milleville and Badenhop, 1980).

Entrapped air may present difficulties in assuring an adequate thermal process with retort pouches. Entrapped air can cause problems in two ways. First, it can expand during processing putting excessive pressure on the pouch seals, possibly to the extent that the pouch integrity is threatened. Second, it can cause a reduction in the rate of heat penetration. The problem of expansion is controlled to a certain extent by the presence of overriding air pressure in the retort vessel for both water and steam-air processing (Whitaker, 1971). The other obvious precaution would be to maintain the entrapped air at a low level (Lampi, 1977). The major concern with entrapped air is its effect on the rate of heat penetration (Nelson and Steinberg, 1956; Beverly et al., 1980), especially with horizontally positioned retort pouches. Berry and Kohnhorst (1983) and Beverly et al. (1980) found an increase in process time needed for equivalent F_o-values as the amount of entrapped air increased.

Huerta-Espinosa (1981) also showed an increase in process time with entrapped air along with movement of the cold spot upward from the geometric center of the pouch.

The purpose of the present study was to examine the magnitude of heat transfer resistances existing between the flowing heating medium and the surface of a food product in institutional size retort pouches. These resistances included the rack design, flow rate of the heating medium, pouch material and entrapped air.

Materials and Methods

Polycarbonate Slab Preparation

Four polycarbonate slabs (two 10 X 9 X 1.0 inch slabs and two 10 X 9 X 1.5 inch slabs; Tuffac, Rohm and Haas, Philadelphia, PA) were used in this investigation. Each slab was equipped with 4 holes (#50 drill, 0.07 inch diameter) to accommodate thermocouples. All thermocouple holes were located in the infinite slab region of the specific polycarbonate slab as determined by comparison of the exact mathematical solutions of the heat penetration equation for the infinite slab and parallelepiped geometries. The computer programs used for this comparison are listed in Appendices A and B for the infinite slab and parallelepiped geometries, respectively. The measured thermocouple positions for the four polycarbonate slabs are listed in Table 3-1. Fig. 3-1 illustrates the thermocouple positioning in a 1.0 inch slab.

Table 3-1. Vertical position of thermocouple holes in polycarbonate slabs.

	Vertical distance from midplane (inches)			
Slab Thickness	1.0 inch		1.5 inch	
Slab number	1	2	3	4
	+0.23	+0.29	+0.38	+0.28
	+0.07	+0.14	+0.19	+0.13
	-0.01	-0.04	0.00	-0.03
	-0.26	-0.26	-0.38	-0.41

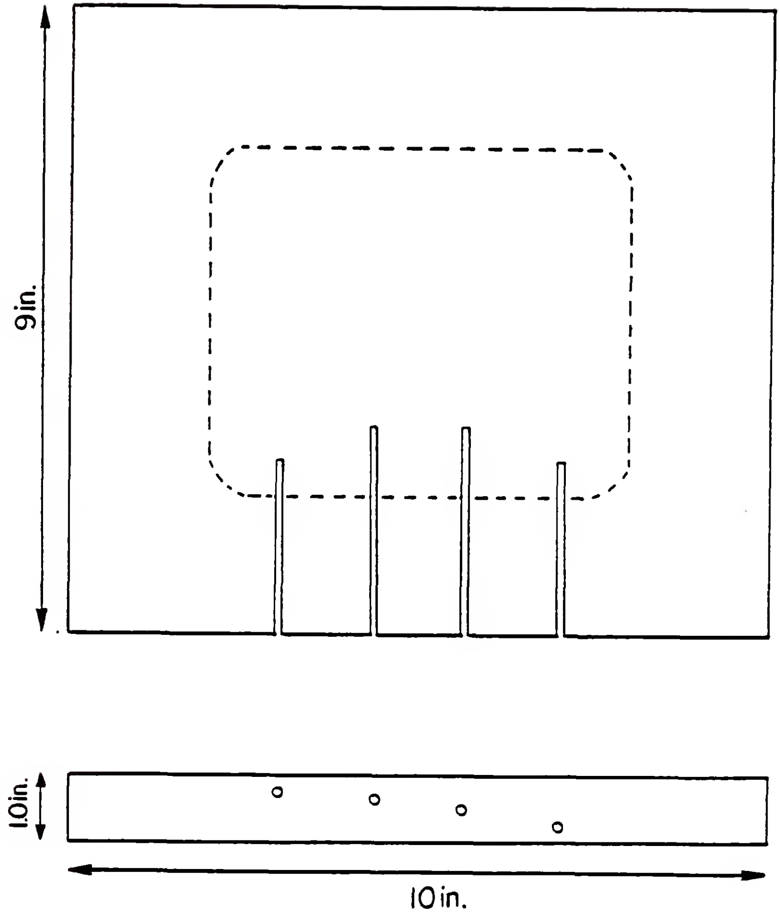


Figure 3-1. Thermocouple placement in a 1.0 inch polycarbonate slab. ----- indicates infinite slab region of the slab midplane.

The polycarbonate slabs were processed with and without the presence of pouch material. For slabs processed without pouch material, 6 inch CNL needle type thermocouples (O.F. Ecklund, Cape Coral, FL) were sealed in the thermocouple holes of the slab with a general purpose silicon caulk (Dow Corning, Midland, MI). For slabs processed in retort pouch material, a commercially available pouch material (0.5 mil PET/ADH/0.5 mil Al foil/4 mil PP; American Can Company, Greenwich, CT) was used. Six inch CNL type thermocouples were introduced into the pouch by means of stuffing boxes (C5.2, O.F. Ecklund, Cape Coral, FL). The pouch was formed with 1/4 inch wide impulse seals (14H/HTV, Vertrod Corp., Brooklyn, NY). The final seal of each pouch was accomplished with a vacuum impulse sealer (Multivac M-3-II, Koch, Kansas City, MO). Each pouch was exposed to 29 inches of vacuum (inches of mercury) for at least 2 minutes prior to sealing. Following the vacuum seal, each pouch was given an additional 1/4 inch cosmetic seal.

Slab Processing

Processing was accomplished in a retort designed and built at the University of Florida specifically for processing institutional size retort pouches. A detailed description of this retort is given by Adams et al. (1983). The heating medium used was flowing pressurized water. The retort was loaded at ambient temperature and was flooded with 270 F water. Two to 3 minutes were required to bring the water up to the processing temperature of 250 F after flooding. Processing continued at 250 F with 10 psi overriding air pressure (25 psig total system pressure) until the slowest heating thermocouple was within 5 F of retort temperature (approximately 245 F), at which time the retort was drained and flooded with cooling water. The cooling water was circulated while being continuously vented and replenished. The appropriate flow rates of the heating medium were maintained during processing for both heating and cooling. All thermocouples were grounded by attaching a ground wire from the stainless steel sheath of the thermocouple to the frame of the retort inside the retort vessel. Temperature data were collected on a recording potentiometer (Digistrip II, Kaye Instruments, Bedford, MA).

The horizontal racking system used for the 1.0 inch polycarbonate slab was identical to that described by Peterson and Adams (1983). The 1.0 inch slabs were positioned in the two rear center positions of the racking system. All positions not containing polycarbonate slabs were filled with institutional size retort pouches containing a 10% (w/w) bentonite suspension in water. The horizontal racking system for the 1.5 inch polycarbonate slabs was similar to the 1.0 inch racking system. A total of six 1.5 inch pouches could be processed at once. The racking system contained 3 racks each able to hold two 1.5 inch pouches. A 3/4 inch channel for the heating medium surrounded each of the racks. The 1.5 inch polycarbonate slabs were processed in the upper and center rear positions in the racking system. All other positions were filled with retort pouches containing a 10% bentonite suspension.

Thermal Diffusivity of Polycarbonate Slabs

Thermal diffusivity of the 1.0 and 1.5 inch polycarbonate slabs was determined by the transient method utilizing the f_h-value of the heating curve (Olson and Jackson, 1942). The polycarbonate slabs were processed in flowing 100% steam (460 lbs/hr), with no pouch material, using the large perforation rack design with no top on the rack. The resulting f_h-value was determined with a computer program using linear regression. This program is listed in Appendix C.

Heat Transfer Resistances Due to Pouch Material, Rack Type, and Flow Rate

A preliminary experiment was performed to determine if the replicate slabs demonstrated significantly different heat penetration behavior. The experimental design also allowed testing of the significance of day to day variation in the operation of the retort. The experiment was performed at Reynolds numbers of 6,000 and 32,000. Reynolds numbers were calculated using the hydraulic diameter of the channels between the racks. Slabs were processed in pouches using confining racks constructed of 16 gauge stainless steel with 3/8 inch holes on 9/16 inch staggered centers.

The statistical design used for the preliminary experiment was a randomized block design with pouch thickness as main blocks and days as sub-blocks. A total of 8 retort runs were completed; each contained two polycarbonate slabs of the same thickness. The 8 runs were completed over a period of 4 days.

The second experiment in this portion of the research utilized the two 1.0 inch polycarbonate slabs. The slabs were processed with and without pouch material for this experiment. Three different rack designs made from 16 gauge stainless steel were used. The first rack type was constructed of perforated stainless steel with 40% open area and large perforations (3/8 inch holes on 9/16 inch staggered centers). The second type had 40% open area and small perforations (1/8 inch holes on 3/16 inch staggered centers). The third type was constructed from a solid stainless steel sheet. The two racks in the one inch racking system that were not being tested (the top and bottom positions) contained the large perforation rack design for all processing trials. Four flow rates were used; the average volumetric flow rates along with the calculated Reynolds numbers are listed in Table 3-2.

A completely randomized split plot design was used for this investigation. Each processing run contained one polycarbonate slab with pouch material and one without pouch material; therefore, pouch material was treated as the sub-plot. Each processing run contained one rack type and was completed at one flow rate; therefore, rack type and flow rate were analyzed as main plots. A total of 24 processing runs were performed, each containing 2 polycarbonate slabs as experimental units. The appropriate division of the degrees of freedom for this experimental design are listed in Table 3-3. The main plots, flow rate and rack design, and the interaction of the two were tested using error A. The sub-plot, pouch material, and interactions of the sub-plot were tested using error B. The response

Table 3-2. Average flow rates used to test effect of pouch material and rack type on heat transfer.

Flow rate (gal/min)	Reynolds number
9.5	2,800
25.1	7,500
60.1	18,000
108.6	32,000

Table 3-3. Division of degrees of freedom for experimental design used to examine effects of the presence of pouch material, confining rack design, and flow rate on heat transfer.

Source	df
Flow	3
Rack	2
Flow*Rack	6
Error A [Run(Flow*Rack)]	12
Pouch	1
Pouch*Flow	3
Pouch*Rack	2
Pouch*Flow*Rack	6
Error B [Pouch*Run(Flow*Rack)]	12
Thermocouple(Pouch*Run(Flow*Rack)	144
TOTAL	191

variables for the experimental design were f_h and f_c, which were calculated by means of a computer program using linear regression (Appendix C).

Entrapped Air

For this portion of the research, the sides of the 1.0 and 1.5 inch polycarbonate slabs were tapered with a general purpose silicon caulk (Dow Corning, Midland, MI). The purpose of this was to give the pouched polycarbonate slabs a shape more closely resembling that of an actual food product. The appropriate amount of air was injected into the corner of a vacuum sealed pouched slab by means of a syringe with a 20 gauge hypodermic needle. The pouch was then resealed. The seals of the pouch were as close to the polycarbonate slab as possible.

Pouched slabs with air were processed in high flow rate pressurized water at 250 F with 10 psi overriding air pressure (25 psig total system pressure). The 1.0 inch slabs with air present were processed in the small perforation confining racks, and the 1.5 inch slabs were processed in the large perforation confining racks.

The actual amount of air present in the pouched slabs was measured after processing by the destructive method (Shappee and Werkowski, 1972). The pouch was opened under water, and the air present was collected in an inverted graduated cylinder. The volume of air was measured with the air in the inverted graduated cylinder at the same level as the surface of the water in the reservoir.

Results and Discussion

Thermal Diffusivity of Polycarbonate Slabs

The thermal diffusivity of the 1.0 and 1.5 inch polycarbonate slabs was determined by processing in flowing 100% steam supported on a sheet of 16 gauge stainless steel with 3/8 inch holes on 9/16 inch staggered centers. Thermal diffusivity was calculated from the f_h-value according to the formula given by Olson and Jackson (1942) for an infinite slab:

$$\alpha = 0.933(A^2)/f_h$$

Where α is the thermal diffusivity, A is the half thickness of the slab, and f_h is the time required for the straight line portion of the heating curve to transverse one log cycle when plotted on semi-log graph paper. The error introduced into the calculated thermal diffusivity values by assuming an infinite slab geometry was 2% for the 1.0 inch slabs and 5% for the 1.5 inch polycarbonate slabs. Table 3-4 contains the calculated thermal diffusivity values for this experiment, the manufacturers specification, and the results of the 1.0 inch slabs processed in high flow rate water (Re=32,000, no pouch material, large perforated racks) from the experiment examining flow rate, pouch material, and rack design. There is a variation of less than 4% between all of these values. Also, the thermal diffusivity value for the high flow rate of water resulted in a value very close to that obtained with flowing 100% steam. This indicated that high velocity water resulted in a heat transfer rate similar to 100% steam

Table 3-4. Thermal diffusivity values obtained for the polycarbonate slabs.

	Thermal Diffusivity[a]
Manufacturer Specification	0.012 in^2/min
100% steam; 1.0 in. slabs	0.0117 ± 0.0002 in^2/min
100% steam; 1.5 in. slabs	0.0121 ± 0.0001 in^2/min
Flowing water (Re=32,000)	0.0119 ± 0.0018 in^2/min

[a] Thermal diffusivity ± 95% confidence interval

for materials with a thermal diffusivity equal to or greater than polycarbonate.

Heat Transfer Resistances Due to Pouch Material, Rack Type, and Flow Rate

This experiment was designed to determine if the presence of pouch material resulted in a significant reduction in heat transfer rate, and to determine if the size or presence of perforations in the confining rack design affected heat transfer. Flow rate was known to affect heat transfer rate (Peterson and Adams, 1983), but was included in this experiment to identify any interactions which may have existed between it and the other two variables. Both heating and cooling data were analyzed using f_h and f_c values as response variables.

A preliminary experiment was conducted to determine if a difference existed between the two 1.0 inch polycarbonate slabs and between the two 1.5 inch polycarbonate slabs, and to determine if there was a significant variation in measured heat transfer rates with time. No significant difference was found between the two slabs of each profile. The p-values found were 0.25 and 0.79 for the 1.0 and 1.5 inch slabs, respectively. There was also no significant day-to-day variation in the measured heat transfer rates. These two findings allowed the experiment examining the effects of pouch material, rack type, and flow rate to be analyzed as a completely randomized split plot design even though the flow rates were experimentally performed as four randomized blocks, and pouch material was used on one polycarbonate slab and not on the other throughout the experiment.

Table 3-2 lists the flow rates used in this experiment along with the calculated Reynolds numbers. The Reynolds numbers for this experiment were chosen to concentrate on the low range of the pouch retort's capabilities, since Peterson and Adams (1983) found the greatest effect on heat transfer rate at the lower Reynolds numbers. Perforations such as those in the racks are known to increase turbulence (Schlichting, 1968), but there is no convenient method to quantify this effect. Therefore, the turbulence levels normally associated with calculated Reynolds numbers is an underestimation of the actual turbulence level for the perforated racks.

Analysis of the data showed that no significant interaction existed between pouch material and any of the other effects examined; therefore, it was appropriate to look at the main effect of the presence of pouch material. The presence of pouch material was not significant during heating, which agreed with the findings of Wornick et al. (1960) and Chapman and McKernan (1963). It should be noted that pouch material may show a measureable effect when pouch contents demonstrate an apparent thermal diffusivity greater than that of polycarbonate. During cooling the effect of pouch material was not significant at the 0.05 level. Because of the large variation of heat penetration parameters associated with the solid racks, the effect of pouch material was examined by excluding the solid rack data from the analysis. Pouch material again demonstrated no significant effect on f_h-values during heating ($p=0.15$) but was statistically significant during cooling ($p=0.04$). The magnitude of this difference was very small. A mean f_c-value of 19.90 minutes with pouch material versus

19.71 minutes with no pouch material was observed. This difference is not large enough to be of concern when performing process time calculations.

The effects of flow rate and rack type were highly significant for both heating and cooling ($p=0.0001$). There was a significant interaction between flow rate and rack type during heating but not during cooling. Fig. 3-2 and 3-3 show f_h and f_c-values, respectively, versus Reynolds number for the different rack designs. During heating, the solid rack resulted in f_h-values 6 to 8 minutes higher than the small and large perforated rack designs. There was a significant difference between the two perforated rack designs but the magnitude was small. The effect of rack design was not as dramatic on cooling rate as it was on heating rate. The solid rack design exhibited f_c-values approximately 2 minutes higher than the f_c-values obtained for the large and small perforated rack designs. The two perforated rack designs did not differ significantly during cooling.

A few simple calculations can show that 1/16 inch of stainless steel should not have had as large an effect on the f_h of the polycarbonate slabs as it did. The probable reason for this increase of f_h-values was that the solid racks had a height of approximately 1-1/16 inches and therefore the polycarbonate slab was not in intimate contact with the stainless steel of the rack. This was coupled with the fact that the racks were closed on the ends and did not allow the processing water to freely enter the rack. An attempt was made to

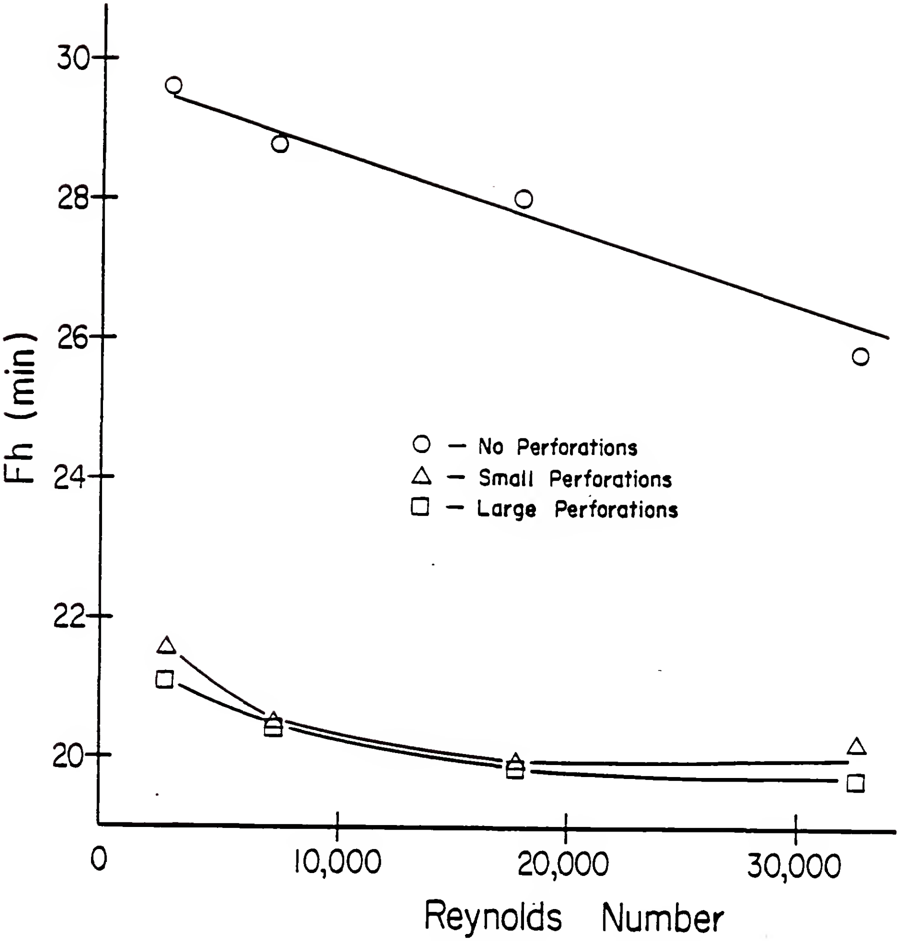


Figure 3-2. Effect of Reynolds number on f_h for each rack type. (No direct contact of pouched slab to solid rack.)

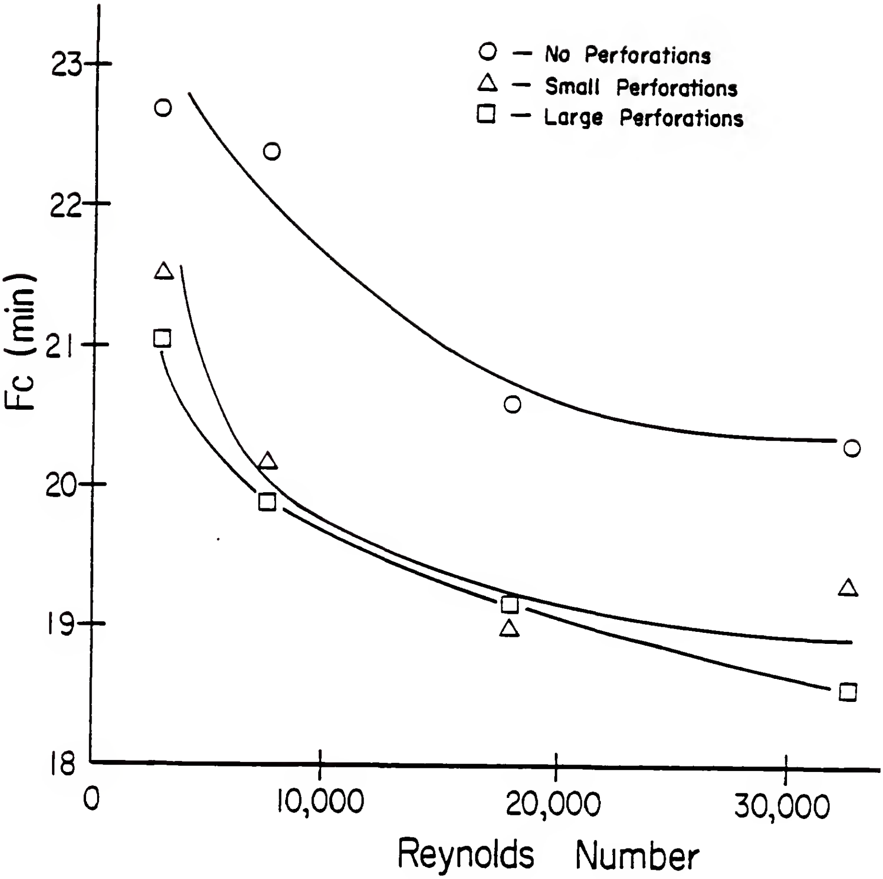


Figure 3-3. Effect of Reynolds number on f_c for each rack type. (No direct contact of pouched slab to solid rack.)

improve the heat transfer rate of the solid racks at the highest water flow rate (Re=32,000). A 1/2 inch channel was opened through the center of the solid racks to allow processing water to enter the rack freely from the ends. When the polycarbonate slabs were in the rear of the retort, the results obtained were identical to those found earlier. This indicated that the 1/2 inch channel was not effective in allowing processing water to flow freely through the rear position. When the polycarbonate slabs were placed in the forward position, close to the entering processing water, the heating rate increased significantly and was less variable. The mean f_h-value observed was 21.69 ± 0.94 minutes. These f_h-values and 95% confidence intervals were still higher than those found for either the large or small perforated rack, but they were much less than the original f_h found without a channel and with the slabs in the rear of the racking system. The open channel increased heat transfer rate but apparently the water entering the rack was at least partially trapped, thereby forming an additional barrier to heat transfer.

Entrapped Air

Initial work with included air was performed with the two 1.0 inch polycarbonate slabs. However, variable results were experienced; entrapped air sometimes caused dramatic changes in the heat penetration characteristics of the slab, while the same amount of air in a replicate trial would cause no effect. This inconsistency was determined to be caused by the air migrating to the sides and corners of the pouch. Also, the stuffing boxes used to introduce the thermocouples into the pouch were very close to the top and bottom of the pouch. By tightening the stuffing boxes to insure an airtight seal, an uneven pouch surface was occasionally produced when air was introduced. These limitations were minimized by rounding the sides of slabs with caulk and producing wells in the caulk to restrict deformation of the sealed pouch by the stuffing boxes.

The first major effect of entrapped air observed with the one inch slabs was the consistent appearance of a broken heating curve. The first portion of the heating curve was identical to that obtained with no air present. The second portion of the heating curve reached an f_h-value of 33 to 34 minutes. Fig. 3-4 illustrates a typical curve obtained along with a replicate run with no air present. The first portion of the broken heating curve indicated that entrapped air had no effect on heat penetration in the initial phase of heating. This phenomenon may have been produced by redistribution of air in the pouch when a certain temperature was reached. This phenomenon may be unique to polycarbonate slabs and may not be observed with a real food products. The second portion of the heating curve consistently reached an f_h of 33 to 34 minutes for all air levels tested. It was felt that this was due to the air expanding to the maximum level allowed by the confining rack system. The racks used for this experiment allowed a total pouch thickness of 1-1/16 inches. Thus, the air on top of the pouch was allowed to expand to a maximum height of 1/16 inch. To test this theory, a forward direction finite difference computer program was developed. The program used an infinite slab model and assumed an infinite Biot number at the surface

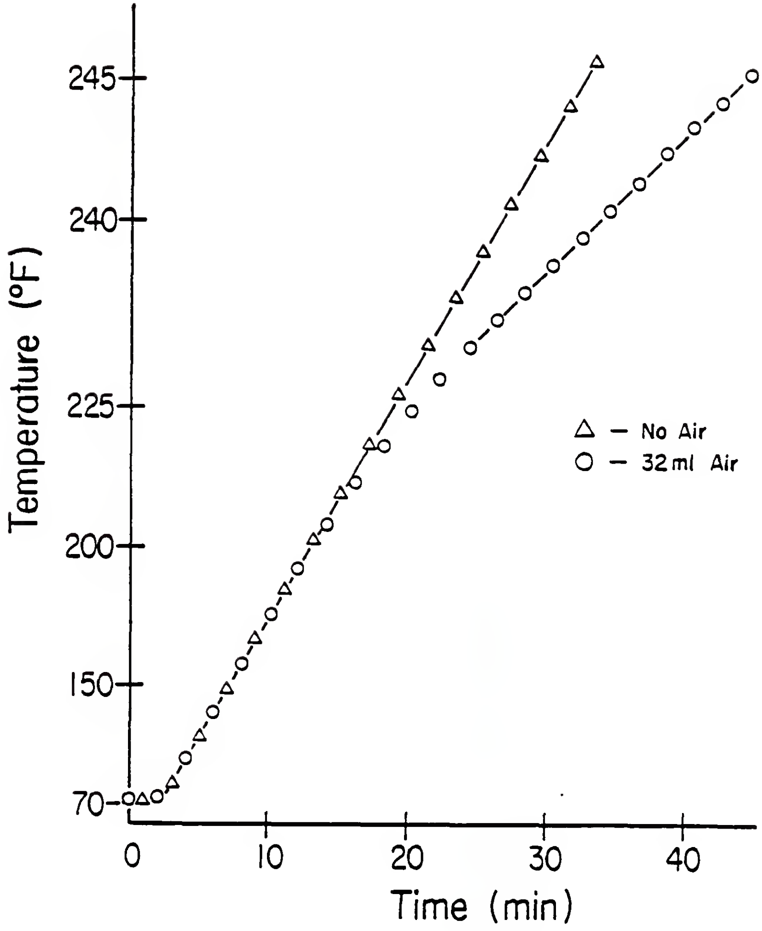


Figure 3-4. Effect of 32 ml air on heating curve of a 1.0 inch polycarbonate slab (center thermocouple position).

of the pouch material. Expansion of both air and water vapor were accounted for through use of the steam table and the ideal gas law. The water present was assumed to have an activity of 1.0. All air was assumed to be on the top surface of the pouch and height of the entrapped air was assumed to be maximal at the center of the polycarbonate slab and to decrease in a parabolic fashion to zero at the edges of the slab. The equation which describes this behavior is

$$z=c+c*x^2*y^2/(a^2*b^2)-c*x^2/a^2-c*y^2/b^2$$

This equation can be integrated and rearranged to give

$$c=9*V/(16*a*b)$$

Using this equation, the height of the air above the center of a slab can be calculated from the volume of air present and the length and width of the slab. Heat transfer through the air layer was assumed to be conductive. The program used the height of the air at the center of the slab for heat penetration calculations. A provision was included in the program for maximum expansion of entrapped air allowed by the confining rack. This program is listed in Appendix D. Using the heat penetration characteristics of the polycarbonate slabs, the program determined a maximum f_h-value of 35 minutes when a maximum expansion of 1/16 inch was used. This agreed very well with the experimentally observed values of 33 to 34 minutes. However, the program did not predict the initial portion of the heating curve observed in Fig. 3-4. A curving line that indicated slower heating than the observed heating curve was predicted by the computer. This curving is what one would expect with expansion of air during the first stages of heating.

The second major effect of entrapped air was a change in the temperature profile within the slab. Fig. 3-5 illustrates all four heat penetration curves obtained for a 1.0 inch polycarbonate slab with 32 ml of air present. The bottom of the slab clearly heated faster than the top, and the thermocouple placed directly above the center (+0.07 inch) had essentially the same heating curve as the one placed directly below the center (-0.01 inch). With no air present, the top and bottom thermocouples in this slab gave nearly identical heating curves and the thermocouple placed +0.07 inch up from the center heated faster than the thermocouple placed -0.01 inch from the center. The air in this pouched slab clearly resulted in a movement of the cold spot upward.

The 1.5 inch polycarbonate slabs were used for further investigation of this cold spot migration. The stuffing boxes used to introduce the thermocouples into the pouched slab were not as close to the top or bottom of the slab as they were in the case of the 1.0 inch slabs, thus a flat surface on top of the slab was achieved. Also, 200 ml of water was added to the pouched slab to help fill the voids in the corners and at the edge of the slab. This aided in confining the entrapped air to the top of the pouched slab. Controls were processed with no air and with 200 ml of water in the pouch. The added water did not affect the heat penetration characteristics of the pouched 1.5 inch slab.

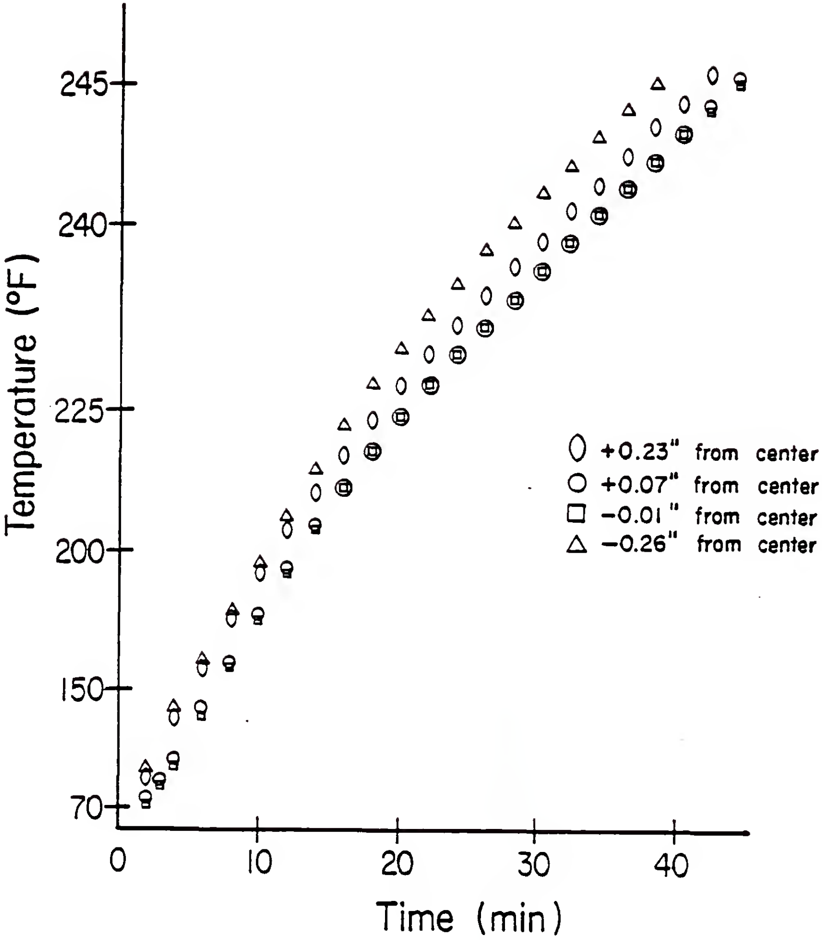
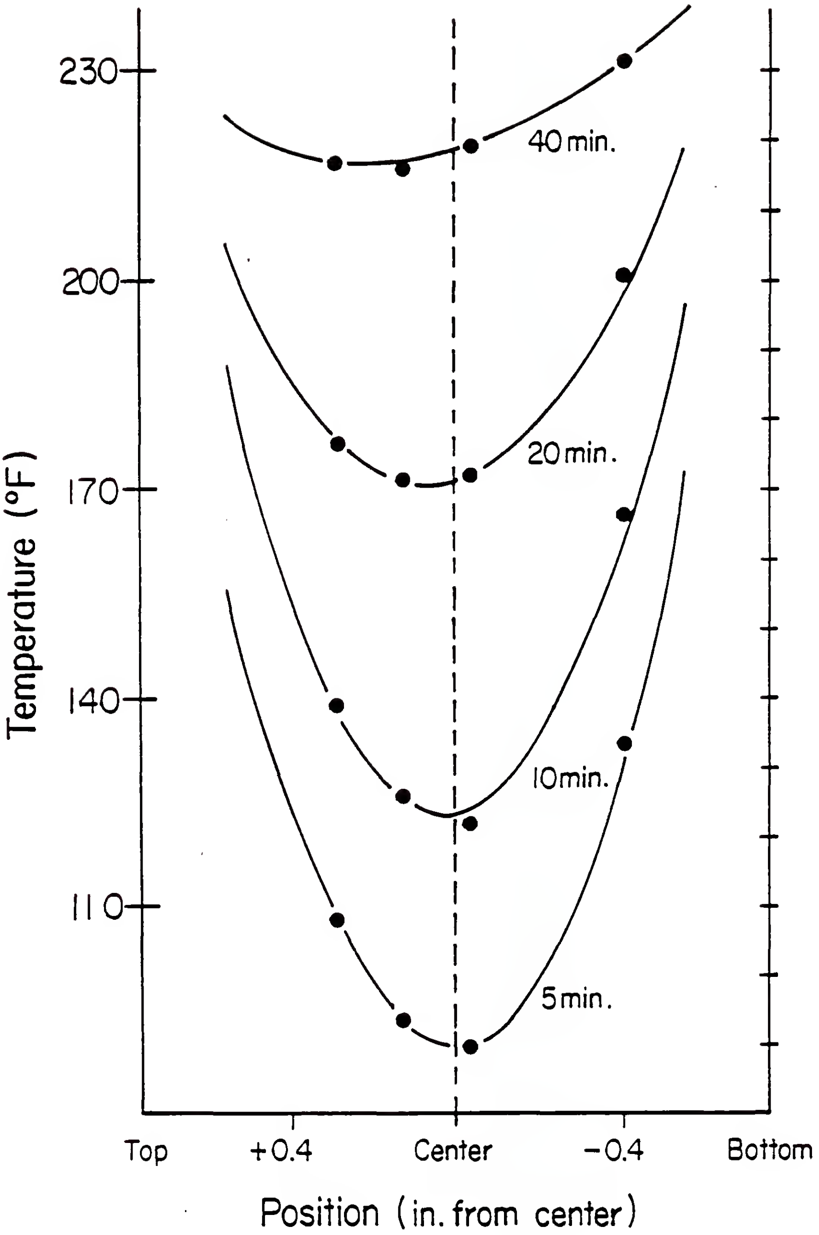


Figure 3-5. Heating curves obtained for all 4 positions in a 1.0 inch polycarbonate slab (slab #1) with 32 ml air present.

A 1.5 inch slab (slab #4) was processed with 98 ml of air present. The temperatures recorded at each of the four thermocouple positions in the slab were fit to a cubic function at various process times. The program used to fit the data to the cubic function employed least squares regression and assumed the lower surface temperature of the slab to be equal to retort temperature. This was a valid assumption since a very large Biot number was found with high flow rate water earlier. Also, if the calculated top surface temperature of the slab was predicted to be greater than the retort temperature, the program repeated the regression using a top surface temperature equal to the retort temperature. This was necessary only in a few instances during the first portion of heating when there was a large temperature gradient in the slab. A listing of this program can be found in Appendix E. The predicted temperature profiles for various processing times can be seen in Fig. 3-6. The bottom of the slab was found to have a higher temperature than the top of the slab at any given process time. It was also apparent that the cold spot moved toward the top of the slab as processing progressed.

The position of the cold spot at a given process time was found by calculating the position of zero slope from the derivative of the predicted cubic function. Fig. 3-7 illustrates the movement of the cold spot from the geometric center of the slab during processing. Initially the cold spot was at the center of the polycarbonate slab. As processing progressed, the cold spot moved upward from the center of the slab to approximately 0.3 inch above the center at the end of processing.

Figure 3-6. Temperature profile within a 1.5 inch polycarbonate slab at various processing times. Curves are from cubic function predicted by least squares. ● = Measured temperatures.



230
200
170
140
110
Temperature (°F)
40 min.
20 min.
10min.
5 min.
Top
+0.4
Center
−0.4
Bottom
Position (in. from center)

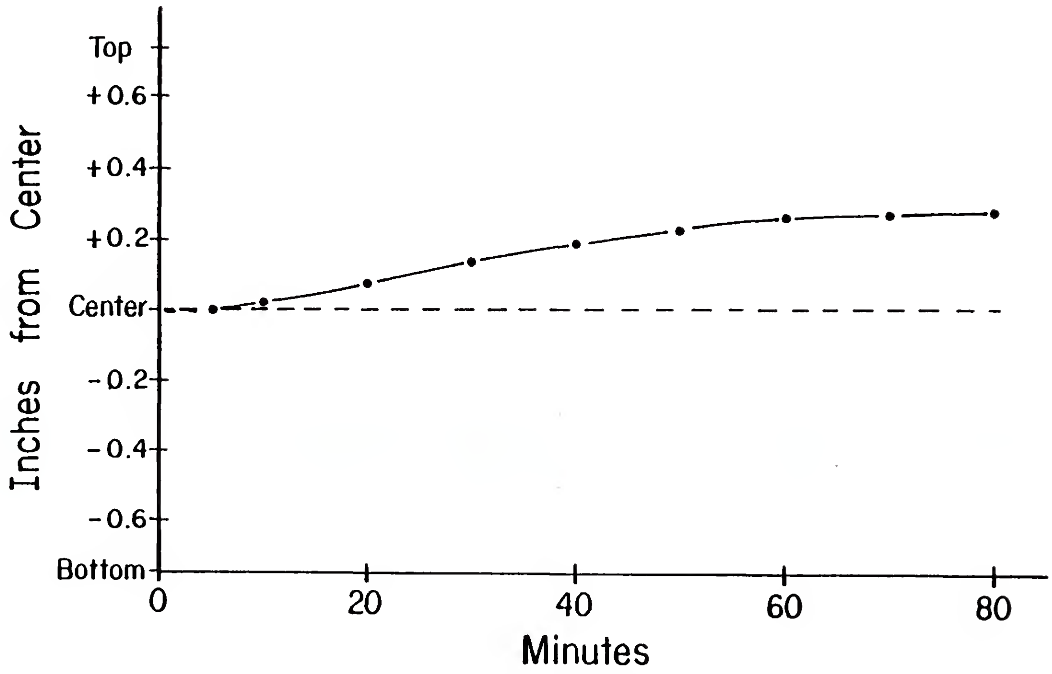


Figure 3-7. Predicted position of cold spot during processing of a 1.5 inch polycarbonate slab with 98 ml of air present.

A replicate pouch with 99 ml of air present was processed to determine if the temperature distribution in the slab and cold spot migration could be repeated and quantified. The replicate resulted in the same general trends experienced in the previous pouched slab (i.e. the bottom of the slab heated faster than the top and the cold spot migrated upward). However the results obtained with the replicate slab were not identical to those obtained with the first slab. The cold spot migration of the replicate slab was less than that of the first slab, migrating a total of 0.16 inch above the center during processing. The finite difference program listed in Appendix D was run under matching conditions to predict cold spot migration in between the two experimentally determined values.

It should be noted that the cold spot did not migrate with the geometric center of the pouch containing entrapped air in any of the three cases examined. Therefore, a self-centering thermocouple positioning method such as that described by Pflug et al. (1963) would not maintain a thermocouple at the cold spot of a retort pouch containing a significant amount of air.

To illustrate the effect of entrapped air on thermal processing, the finite difference program was used to simulate an actual process with various amounts of air present. The results of this simulation are presented in Table 3-5. Increasing the amount of entrapped air from 5 ml to 50 ml with a 10 X 9 X 1.5 inch pouch dropped the center point F_o from 6.42 to 1.69 with a maximum expansion of 1/16 inch allowed by the confining rack system. The F_o received by the cold

Table 3-5. Effect of entrapped air and maximum expansion allowed by confining rack system on F_o received by a 1.5 inch polycarbonate slab with a process time of 70 minutes (includes 3.0 minute come up time).

ml Air	Maximum Expansion	Time to reach maximum expansion	Center F_o[a]	Cold spot F_o[a]
5	1/16 in.	———[b]	6.42	6.41
25	1/16 in.	———	2.97	2.69
50	1/16 in.	38 min.	1.69	1.50
100	1/16 in.	2 min.	1.31	1.19
50	1/8 in.	———	1.56	1.25
100	1/8 in.	57 min.	0.63	0.41

[a] Calculated by improved general method. Reference temperature = 250 F; Z = 18 F.

[b] Maximum allowed expansion not reached during processing.

spot was less than that received by the center in all cases; however, the effect is not as dramatic as that caused by increasing the amount of air present. Also illustrated in Table 3-5 is the effect of the maximum expansion allowed by the confining rack system. In some cases, an increase in the maximum expansion allowed can have an effect as dramatic as increasing the amount of entrapped air present. Clearly the presence of air, even with a confining rack, can substantially reduce the achieved F_o-value to the point where underprocessing of potential health significance may occur.

Summary and Conclusions

A number of conclusions can be drawn from the results of this experiment. First, it was discovered that water at a sufficiently high flow rate resulted in a surface heat transfer coefficient which was sufficiently high to give a heat transfer rate equal to that obtained with 100% steam.

Investigation of the rack design determined that the two perforation sizes used showed no practical difference in rate of heat penetration. The solid rack design, however, did show a significant decrease in the rate of heat transfer when there was a gap between the product and the rack. The results obtained suggest that it is important to insure intimate contact between the pouch and the metal plates of a solid rack as suggested by Milleville and Badenhop (1980). Flow rate of the processing medium was also shown to have a significant effect on heat penetration rate.

Entrapped air was found to have a very large effect on heat penetration rate. The effect of entrapped air was also difficult to quantify. Entrapped air resulted in two major effects. First, heat penetration rate into the retort pouch was severely reduced. Second, the cold spot of the pouch tended to migrate upward during processing. The reduction in heat transfer rate as the amount of air increased had a greater effect on the total thermal process received by the pouch contents than did cold spot migration. When entrapped air was present, the maximum expansion allowed by the confining rack system was an important factor. For optimum heat transfer this maximum expansion should be kept to a minimum. Entrapped air could present a potential health hazard in retort pouches due to its resistance to heat transfer and to its transitory nature.

CHAPTER IV
THERMOCOUPLE GROUNDING IN RETORT POUCHES

Introduction

Accurate measurement of thermal processing parameters is necessary to obtain a valid calculated process time for the sterilization of canned and pouched foods. The validity of these parameters is directly related to the accuracy of the temperature measurements taken during a heat penetration test. Current thermocouple techniques used in the food industry have been developed for cans and glass containers and work well for those containers. With the advent of retort pouches, some temperature measurement problems have been observed with these standard techniques. Davis et al. (1972) experienced temperature measurement errors in retort pouches as large as 20 F when using copper-constantan wire thermocouples. They solved this problem by using enamel-coated thermocouple wire and grounding the measuring junction of the thermocouple to the ground of the recording potentiometer. Pflug (1975) experienced similar problems and solved them in the same manner. Peterson and Adams (1983) used grounded thermocouples successfully; however, they experienced problems when using ungrounded thermocouples (unpublished data).

Temperature measurement errors in retort pouches are usually found to be one of two types or a combination of both. The first and most common error appears as a tailing up or down of the straight line portion of the heating curve. This effect is similar to what is observed when a heating curve is plotted with an erroneous retort temperature. The other error encountered is erratic jumps up or down in the recorded temperature. These errors can be very severe, often resulting in recorded temperatures well above the actual retort temperature. The occurrence of these errors is inconsistent and the magnitude of the error will probably be different for each heat penetration test. If errors occur, they usually become apparent as the temperature of the pouch contents approaches within 10 to 15 F of the retort temperature.

The purpose of this research was to examine the nature and occurrence of these temperature measurement errors in retort pouches, and to evaluate the effectiveness of thermocouple type and methods of grounding in alleviating these errors.

Materials and Methods

Two 10 X 9 X 1 inch polycarbonate slabs (Tuffac, Rohm and Haas Co., Philadelphia, PA) were used. Each slab was equipped with 4 holes (#50 drill, 0.07 inch diameter) at various heights in the slab (slabs 1 and 2 in Table 3-1). The thermocouple holes were located in the infinite slab region of each slab as determined by comparing results from the exact mathematical solutions of the heat conduction equations for the infinite slab and parallelepiped geometries, as previously discussed in Chapter 3.

The polycarbonate slabs were processed in commercially available retort pouch material (0.5 mil PET/ADH/0.5 mil Al foil/4 mil PP) supplied courtesy of the American Can Company (Greenwich, CT). The pouch material was formed into a pouch with 1/4 inch wide impulse seals (14H/HTV, Vertrod Corp., Brooklyn, NY). The thermocouples were introduced into the pouch by means of stuffing boxes (C5.2, O.F. Ecklund, Cape Coral, FL). The final seal of each pouch was accomplished with a vacuum impulse sealer (Multivac M-3-II, Koch, Kansas City, MO). Each pouch was subjected to 29 inches of vacuum (inches of mercury) for at least 2 minutes prior to sealing. Following the vacuum seal each pouch was given an additional cosmetic seal.

Thermocouple Types

Four types of copper-constantan (Type T) thermocouples were used: 1) A 6 inch CNL needle thermocouple (O.F. Ecklund, Cape Coral, FL), consisted of 30 gauge thermocouple wire inside a 1/16 inch O.D. stainless steel tube. The measuring junction was formed by soldering the thermocouple wires and stainless steel tube together·approximately 1/16 inch back from the end. 2) A 6 inch isolated CNL needle thermocouple (O.F. Ecklund, Cape Coral, FL) was identical to the standard CNL type except that the measuring junction was not in electrical contact with the stainless steel tube; therefore, the stainless steel tube was a true electrical shield. 3) 30 and 4) 40 gauge wire thermocouples (matched, teflon coated copper and constantan thermocouple wire; Omega Engineering, Stamford, CT) were fused together to form the measuring junction. An extra copper wire of the same gauge was included in the fusion to provide a means of grounding the measuring junction. The 40 gauge thermocouple wire was very fragile; therefore, after approximately 6 inches of the wire was used, the 40 gauge wire was soldered to 24 gauge thermocouple wire (Thermo Electric, Saddle Brook, NJ). This soldered connection was secured to the polycarbonate slab using a cement made of polycarbonate shavings dissolved in dichloromethane. The wire thermocouples were held in place on the slab with a general purpose sealant silicon caulk (Dow Corning, Midland, MI). Previous experience had indicated that when more than one wire was extended through a stuffing box, a loss of vacuum in the pouch could result during processing. This problem was solved by using electrical shrink tubing in conjunction with silicon caulk at the point where the thermocouple wires entered the stuffing box. The wire thermocouples terminated outside the pouched polycarbonate slab at a female thermocouple connector (C-7, O.F. Ecklund, Cape Coral, FL), and the copper ground wire terminated at a small copper alligator clip.

Copper-constantan teflon-coated thermocouple wire (24 gauge, Thermoelectric, Saddle Brook, NJ) was used from the measuring potentiometer into the retort vessel where it was terminated with a male thermocouple connector (C-6, O.F. Ecklund, Cape Coral, FL). The back of the male connectors and female connectors (wire thermocouples only) were filled with silicon caulk (Dow Corning, Midland, MI) to prevent water intrusion.

Grounding Methods

Three different grounding methods were used: a retort grounding method, a potentiometric grounding method, and no ground. The retort grounding method was accomplished by attaching the ground wire from the 30 and 40 gauge wire thermocouples to the frame of the retort by means of an alligator clip. The non-isolated and isolated sheathed thermocouples were grounded to the frame of the retort by a copper wire having two alligator clips. One end of the ground wire was connected to the portion of the stainless steel sheath that extended outside the pouch; the other end was attached to the frame of the retort. Thus, for all the retort grounded thermocouples except for the isolated type, the measuring junction was grounded to the frame of the retort. The measuring junction of the isolated thermocouple was not grounded; however, the stainless steel shield surrounding it was. For the potentiometric grounding method, a copper wire was connected to the positive lead at the measuring potentiometer and grounded to the frame of the retort. For the potentiometric grounding method and no ground, the alligator clips on the 30 and 40 gauge wire thermocouples used for the retort grounding method were wrapped in glass cloth electrical tape.

Processing

The retort used in this study was designed and built at the University of Florida for processing institutional size retort pouches (Adams et al., 1983). One inch confining stainless steel racks constructed of 16 gauge stainless steel with 40% open area (3/8 inch holes on 9/16 inch staggered centers) were used for this study. Two of the total eight positions in the racking system contained pouched polycarbonate slabs; all other positions contained pouches filled with a 10% bentonite suspension. The pouched polycarbonate slabs were repeatedly processed until loss of vacuum occurred. At that point the slabs were repouched as described earlier.

This study examined two heating media; flowing pressurized water and a steam-air mixture. For pressurized water processing the retort was loaded at ambient temperature and processing water, preheated to 270 F, was introduced into the pressurized retort. The slabs were processed at 250 F with a come up time of approximately 2 to 3 min. The processing water was recirculated at a rate of 110 gal/min (Reynolds number = 33,000), and an overriding air pressure of 10 psi was used (total system pressure of 25 psig). The polycarbonate slabs were processed until the slowest heating thermocouple had reached 245 F at which time the processing water was drained and the retort was flooded with cooling water. The cooling water was circulated while being continuously vented and replenished, and required less than 10 min. to reach a temperature within 1 F of the final temperature.

For steam-air processing, a mixture of 90% steam and 10% air was used. The retort was filled with the pouched polycarbonate slabs at ambient temperature. The pouches were processed in 100% steam for the first 1.5 minutes, at which time the air pressurization was initiated. After this venting and come up, the slabs were processed at 250 F, with a total system pressure of 18.4 psig, and a flow rate of 462 lbs steam-air/hour (394 lbs steam/hour) resulting in a Reynolds number of 4,800.

Experimental Design

This experiment was designed to give comparisons between thermocouple type and grounding methods without confounding any main effects or interactions. Two assumptions were made for this design. The first assumption was that the 2 one inch slabs were identical as shown to be a valid assumption in Chapter 3. Second, it was assumed that different positions in the same slab would result in the same f_h-value. Theoretically, this is a reasonable assumption.

Table 4-1 shows the experimental design used for the first replicate of the pressurized water cook portion of the experiment. Slab numbers in Table 4-1 correspond to those listed in Table 3-1. Thermocouple holes were numbered sequentially from top to bottom for each slab. The same design was used for the second replicate. The major difference was that the isolated and non-isolated thermocouples were placed in slab 2 and the 30 and 40 gauge wire thermocouples were placed in slab 1. The thermocouple hole within a slab also contained a different thermocouple type for the second replicate. For example,

Table 4-1. Experimental design for first replicate of pressurized water cook.

	Slab 1				Slab 2			
	Thermocouple Type				Thermocouple Type			
Retort Run	I(1)[a]	NI(2)	I(3)	NI(4)	40(1)	30(2)	40(3)	30(4)
1	NO[b]	NO	PO	RT	NO	NO	PO	RT
2	PO	PO	NO	RT	PO	PO	NO	RT
3	RT	RT	PO	NO	RT	RT	PO	NO
4	RT	PO	NO	NO	RT	PO	NO	NO
5	RT	NO	PO	PO	RT	NO	PO	PO
6	PO	NO	RT	RT	PO	NO	RT	RT

[a] I = Isolated sheathed thermocouple type.
NI = Non-isolated sheathed thermocouple type.
30 = 30 gauge wire thermocouple.
40 = 40 gauge wire thermocouple.
( ) = Slab thermocouple hole number.

[b] NO = No ground.
PO = Potentiometric grounding method.
RT = Retort grounding method.

thermocouple holes number 1 and 3 for slab 1 contained the isolated thermocouple type during the first replicate. For the second replicate the isolated thermocouple type would be found in holes number 2 and 4 in slab 2. This experimental design was repeated for steam-air processing. This design yielded eight heating curves for each combination of thermocouple type and grounding method.

Data Analysis

Temperature histories for both pressurized water and steam-air heating and for pressurized water cooling were recorded with a data logger (Digistrip II, Kaye Instruments, Bedford, MA). The potentiometer was equipped with 120 dB common mode noise rejection circuitry. The data was analyzed using non-linear regression analysis of the exponential function describing the straight line portion of the heating or cooling curve (Statistical Analysis System, release 79.6, SAS Institute, Cary, NC). The model used for heating data was

$$(T_{rh}-T)=C*EXP(-2.302585*t/f_h)$$

where C is the intercept of the straight line portion of the heating curve at time zero. The model for cooling data was the same as that for heating data with the necessary adjustments.

In all cases, 18 temperature values, each separated by one minute, were analyzed for both heating and cooling. For heating, the last of the temperature values analyzed was 5 F below retort temperature, or approximately 245 F. The last of the cooling values analyzed was 10 F above the cooling retort temperature, or approximately 80 F. Heating and cooling retort temperatures were determined by averaging the temperature values of two thermocouples located at the exit of the retort racking system.

Statistical analysis of the resulting heat penetration data was accomplished using the Statistical Analysis System (release 79.6, SAS Institute, Cary, NC). Response variables analyzed were both f_h or f_c and the residual sum of squares generated by the non-linear regression performed on each heating or cooling curve. The residual sum of squares was appropriate to use since all regressions contained an identical number of observations.

Results and Discussion

Non-linear regression was chosen for analysis of the various heating curves as opposed to a log transformation followed by linear regression. Non-linear regression avoided the problem of changes in the error distribution around different temperature observations which would be experienced with a log transformation of the temperature data.

Fig. 4-1 through Fig. 4-3 illustrate heating curves obtained for various residual sum of squares values. A very good straight line was obtained with residual sum of squares values of 0.57 or less (Fig. 4-1). Deviations from the straight line became apparent when residual sum of squares equaled 0.75 and 3.00 (Fig. 4-2 and 4-3, respectively). No figures with a residual sum of squares greater than 3.00 are presented because it was felt that Fig. 4-2 and 4-3 were unacceptable heating curves for polycarbonate slabs. The typical problem observed

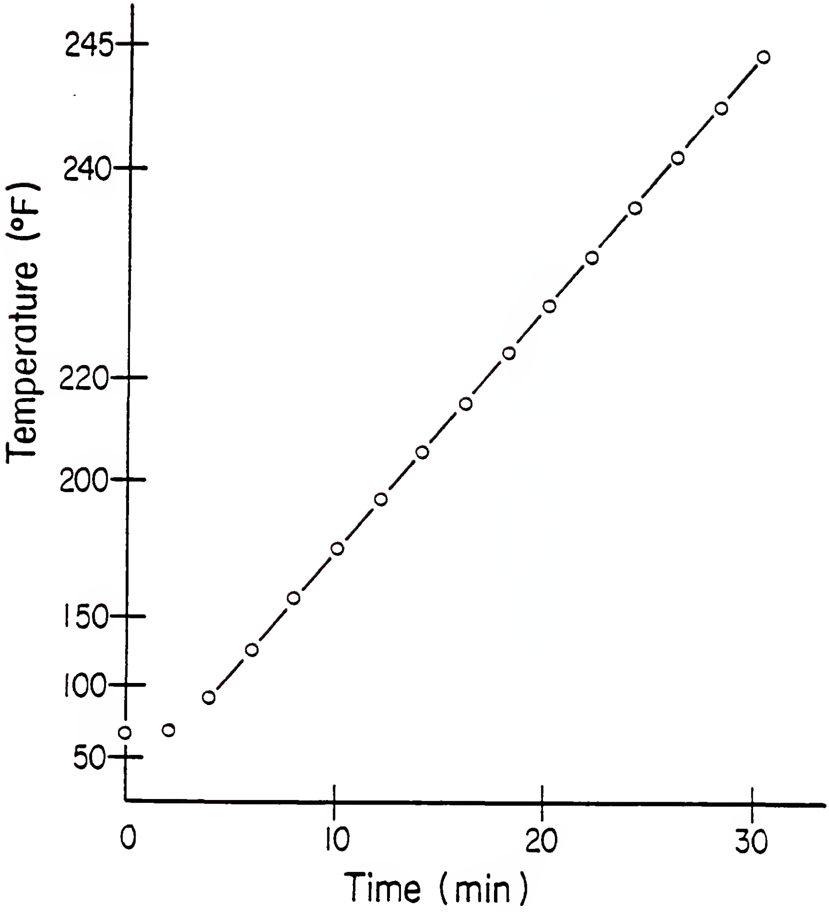


Figure 4-1. Heating curve with residual sum of squares equal to 0.57.

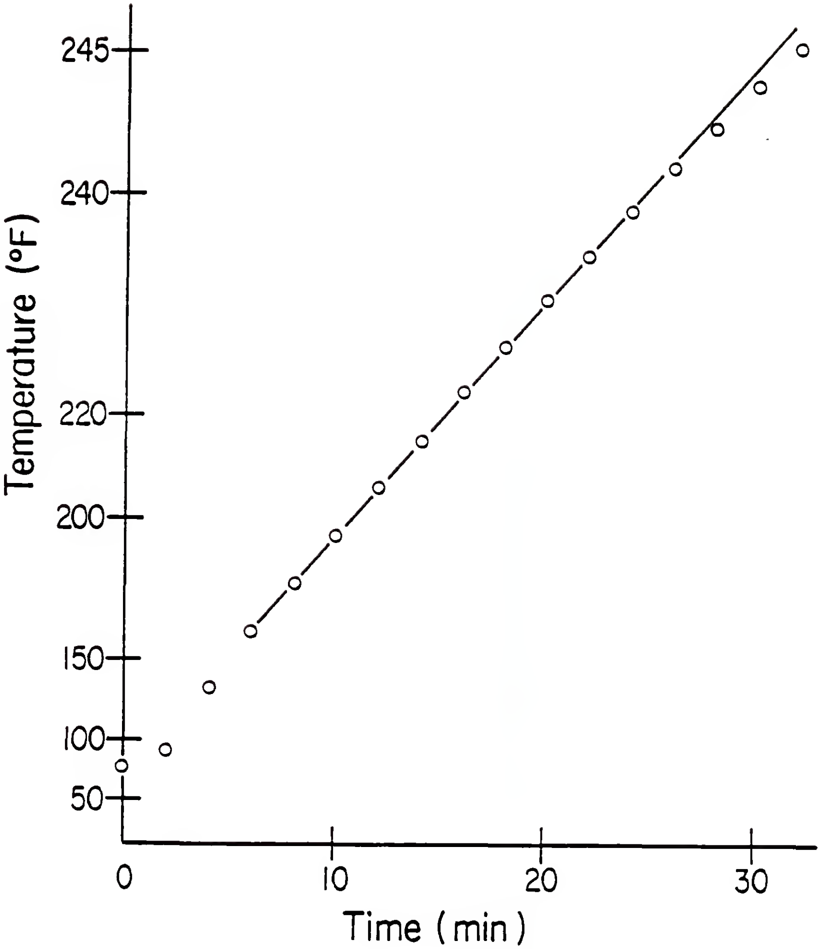


Figure 4-2. Heating curve with residual sum of squares equal to 0.75.

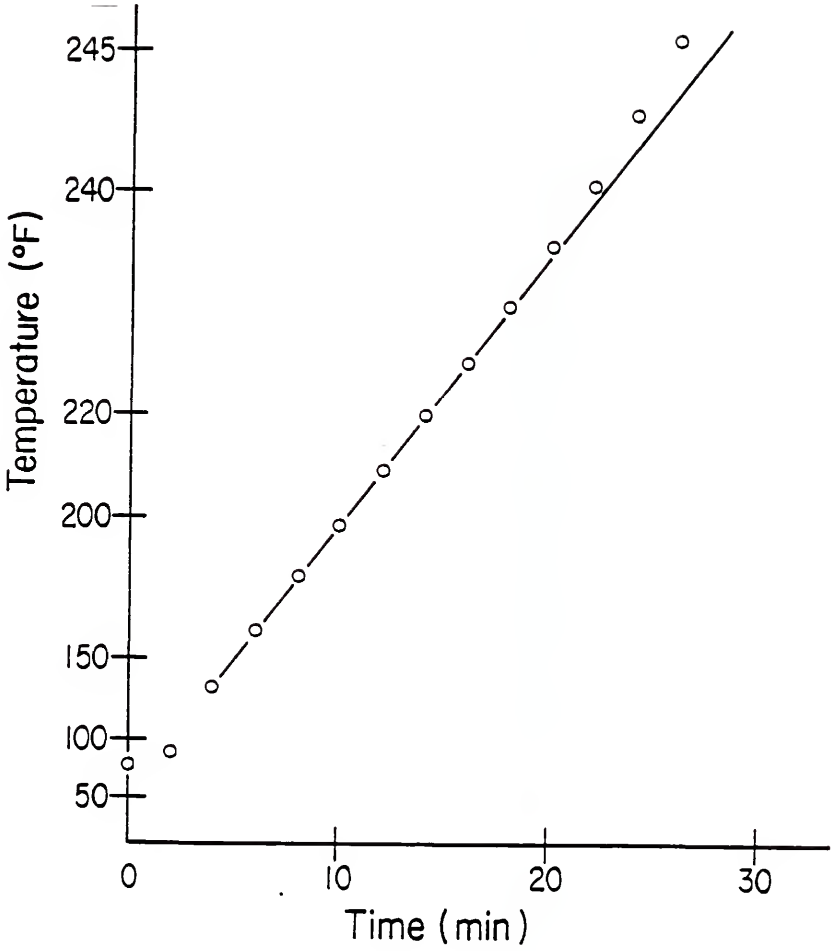


Figure 4-3. Heating curve with residual sum of squares equal to 3.00.

as the residual sum of squares increased was a tailing off or tailing up of the straight line portion of the heating curve as the measured temperature approached retort temperature (Fig. 4-2 and 4-3). Since values plotted were the differences between pouch and retort temperatures, plotting at a higher or lower retort temperature would straighten out these lines. The retort temperature measured by thermocouples in the retort was known to be accurate since those thermocouples were checked in an oil bath at 250 F and were found to agree within 0.3 F. This accuracy in measurements was coupled with the observation that the same thermocouple measuring a slab temperature in the retort did not consistently give the same type or magnitude deviation from the straight line portion of the heating curve between replicate processing runs. Thus, this effect was considered real and not just an artifact created by errors in temperature measurement. Additionally, since the rate of temperature change (slope) was the dependent parameter of interest, the effect of error in absolute temperature value measured (±1.5 F; potentiometer specifications) would be minimized.

Pressurized Water Heating

The residual sum of squares of the different thermocouple types and grounding methods for heating with pressurized water are presented in Fig. 4-4. Statistical analysis of the data revealed a significant interaction between thermocouple type and grounding method. The isolated thermocouple resulted in acceptable heating curves with low residual sum of squares in all cases; thus, data obtained from this

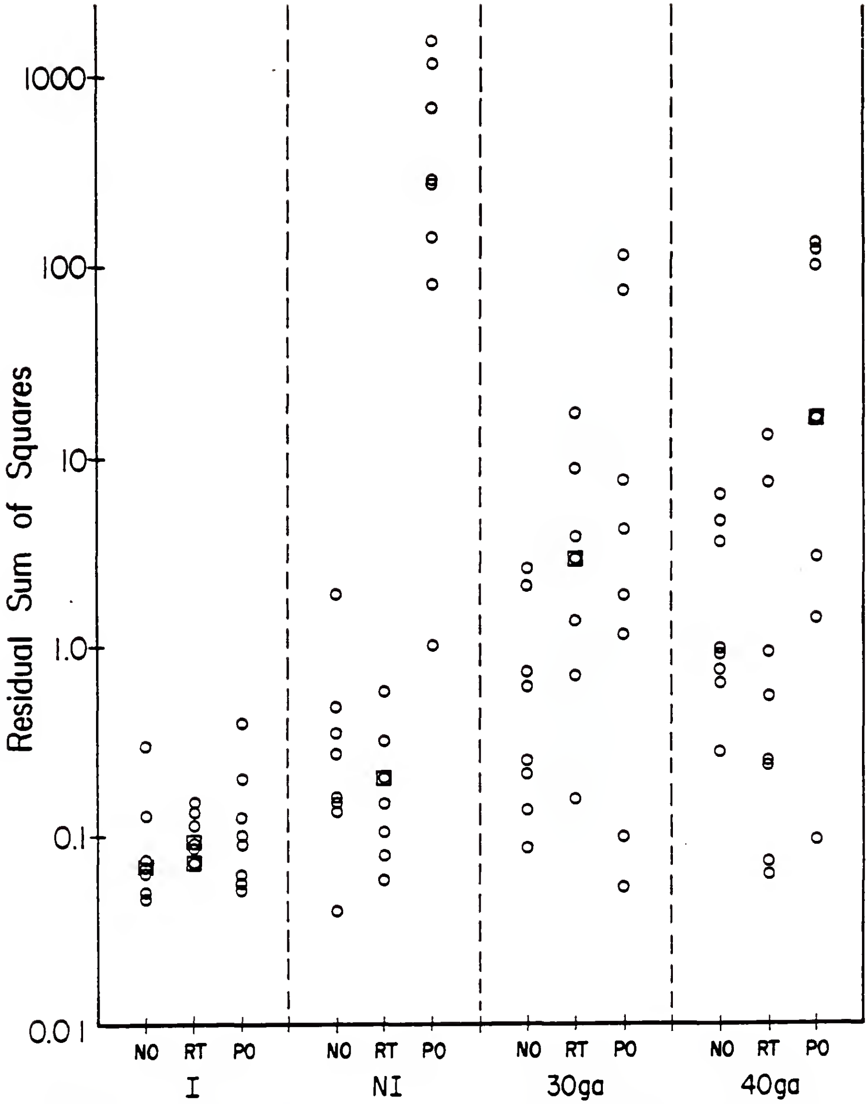


Figure 4-4. Residual sum of squares obtained for pressurized water heating. I = Isolated thermocouple; NI = Non-isolated thermocouple; 30ga = 30 gauge wire thermocouple; 40 ga = 40 gauge wire thermocouple; NO = No ground; RT = Retort ground method; and PO = Potentiometric ground method. ◘ indicates 2 points at the same residual sum of squares value.

type of thermocouple were not dependent on the type or presence of ground. For the other three thermocouple types, grounding at the positive lead of the measuring potentiometer resulted in very high residual sum of squares with a high level of variation. This indicated that the heating curves obtained did not fit a straight line. The heating results using the potentiometric grounding method often showed temperatures near the end of processing as high as 15 F above retort temperature. Apparently, grounding at the positive lead of the recording potentiometer led to more problems than it solved in the processing system used. This method of grounding was included in the experiment at the suggestion of the manufacturer of the recording potentiometer.

The non-isolated thermocouple type gave fairly good results with both the retort ground and no ground. Grounding in the retort resulted in a smaller spread in the data than did no ground; however, there was not a significant difference between the two methods. Previous work with non-isolated thermocouples which were not grounded resulted in more variable results. In this experiment, all but one of the non-isolated thermocouples without a ground gave an acceptable regression fit of the data. Previous work with a 10% bentonite suspension and pouched seafood revealed the tailing data illustrated in Fig. 4-2 and 4-3 and also instances of instability in temperature measurement which were not observed in this experiment. A typical example of this instability found with a 1.0 inch thick pouched bentonite suspension is shown in Fig. 4-5. The previous work indicated that the failures observed should have occurred at a rate of

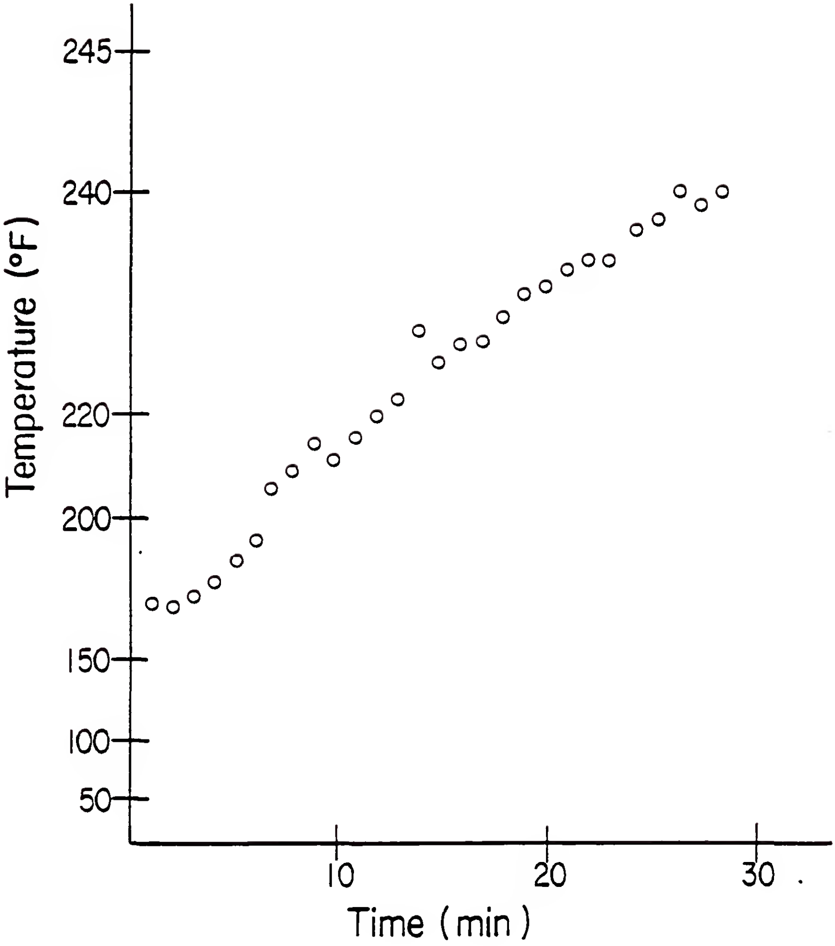


Figure 4-5. Heating curve illustrating instability in temperature measurement.

approximately 3 out of 8 heating curves. Peterson and Adams (1983), working with a 10% bentonite suspension, also revealed that the retort grounding method with the non-isolated thermocouple type essentially eliminated the problems.

The 30 and 40 gauge wire thermocouples gave similar results for each grounding method. In each case, the retort grounding method resulted in a greater degree of scatter in the residual sum of squares values than did the no grounding method (Fig. 4-4). This was an unexpected result and was contrary to findings of Pflug (1975). With wire thermocouples, both the retort grounding method and the no ground method resulted in a large percentage of heating curves which did not have an acceptable fit of the regression equation, especially when compared to the isolated thermocouple type.

Statistical analysis using Duncan's multiple range test of the residual sum of squares for the pressurized water cook demonstrated no significant difference at the 0.05 significance level between thermocouple types and grounding methods with one exception. The non-isolated CNL thermocouple coupled with the potentiometric grounding method was significantly different from all other combinations. Even though there was not a statistically significant difference, there was a practical difference between the methods as illustrated in Fig. 4-4. The low degree of scatter in the residual sum of squares for the isolated and grounded non-isolated thermocouples would suggest a greater confidence in these methods than those demonstrating the larger scatter in data.

In addition to the consideration of how well the regression equation fit the heat penetration data, one must be concerned with the f_h-value obtained from the regression. An acceptable regression fit is inconsequential if the f_h-value obtained is erroneous. Table 4-2 summarizes the mean f_h-values observed with the pressurized water cook. The f_h-value obtained should be approximately equal to 20 minutes, which can be calculated from the thermal diffusivity of the polycarbonate slab (Olson and Jackson, 1942). The conclusions drawn from the f_h-values obtained agreed quite well with those found in analysis of the residual sum of squares. The isolated thermocouple gave acceptable f_h-values independent of the grounding method used and the non-isolated thermocouple type gave acceptable results with no ground and the retort grounding method. The 40 gauge wire thermocouple with no ground gave an f_h-value close to that expected; however the 95% confidence interval was large in comparison to that of the acceptable isolated and non-isolated thermocouple types. The 30 and 40 gauge wire thermocouples using the retort grounding method gave lower f_h-values than were expected. By far the best choice for thermocouple type is the isolated type, since it gave the expected f_h-value with a very small 95% confidence interval independent of the type of grounding method used.

Steam-air Heating

Fig. 4-6 contains the results of the residual sum of squares for each thermocouple type and grounding method for heating with 90% steam and 10% air as the processing media. These results are essentially

Table 4-2. Mean f_h-values found for pressurized water heating.

Thermocouple Type	Grounding Methods[a,b] No Ground	Retort Method	Potentiometric Method
Isolated	19.82 ± 0.35^{AB}	20.08 ± 0.31^{AB}	19.81 ± 0.43^{AB}
Non-isolated	19.12 ± 0.71^{AB}	19.87 ± 0.57^{AB}	9.56 ± 4.00^{D}
30 gauge	21.46 ± 3.05^{A}	18.05 ± 1.06^{B}	17.17 ± 3.93^{B}
40 gauge	19.50 ± 1.73^{AB}	18.08 ± 0.85^{B}	14.24 ± 2.04^{C}

[a] Mean f_h-value.± 95% confidence interval.

[b] Means with same letter are not significantly different (Duncan's Multiple Range Test, $p \leq 0.05$).

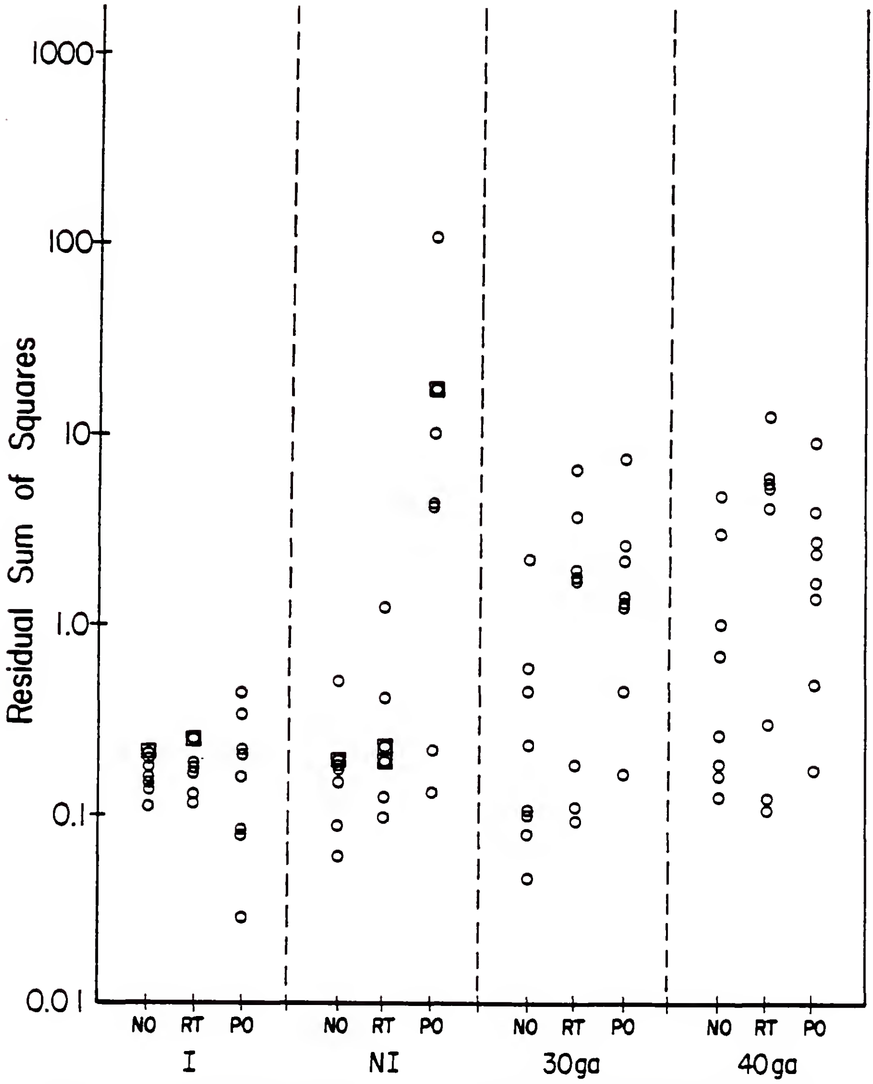


Figure 4-6. Residual sum of squares obtained for heating with 90% steam, 10% air. I = Isolated thermocouple; NI = Non-isolated thermocouple; 30ga = 30 gauge wire thermocouple; 40ga = 40 gauge wire thermocouple; NO =No ground; RT= Retort ground method; and PO = Potentiometric ground method. ◘ indicates 2 points at the same residual sum of squares value.

identical to those found with the pressurized water cook. Overall, the steam-air cook residual sum of squares results demonstrated less scatter than those obtained with the pressurized water cook. The isolated thermocouple type with the potentiometric ground, method and the non-isolated thermocouple type with the retort ground method, displayed more variation than with the pressurized water cook; however, the values were still, for the most part, acceptable.

The mean f_h-values obtained for steam-air heating were less variable for isolated and non-isolated thermocouple types and generally more variable for the 30 and 40 gauge wire thermocouple types when compared to f_h-values obtained for pressurized water heating. This can be seen by comparing the size of the 95% confidence intervals in Tables 4-2 and 4-3. As in the pressurized water cook, the isolated thermocouple with any ground type and the non-isolated thermocouple with the retort ground method or no ground resulted in the expected f_h-value. The 30 gauge wire thermocouple with no ground gave an f_h-value close to the expected value of 20 minutes, but had a fairly large 95% confidence interval.

Cooling Data Analysis

Cooling data obtained from the pressurized water cook was analyzed in the same manner as the heating data. The residual sum of squares results for cooling can be seen in Fig. 4-7. Unlike the heating results, cooling data did not show a significant interaction between thermocouple type and ground method. Additionally, there was not a statistically significant difference between main effects of

Table 4-3. Mean f_h-values found for steam-air heating.

Thermocouple Type	Grounding Methods^{a,b} No Ground	Retort Method	Potentiometric Method
Isolated	20.45 ± 0.24^{CD}	20.52 ± 0.31^{CD}	20.54 ± 0.26^{CD}
Non-isolated	20.21 ± 0.59^{CD}	20.38 ± 0.50^{D}	16.54 ± 2.74^{CD}
30 gauge	20.90 ± 1.04^{BCD}	26.00 ± 4.80^{ABC}	25.32 ± 5.18^{AB}
40 gauge	21.78 ± 4.02^{BCD}	29.46 ± 7.40^{A}	28.83 ± 8.58^{A}

[a] Mean f_h-value ± 95% confidence interval.

[b] Means with same letter are not significantly different (Duncan's Multiple Range Test, $p \leq 0.05$).

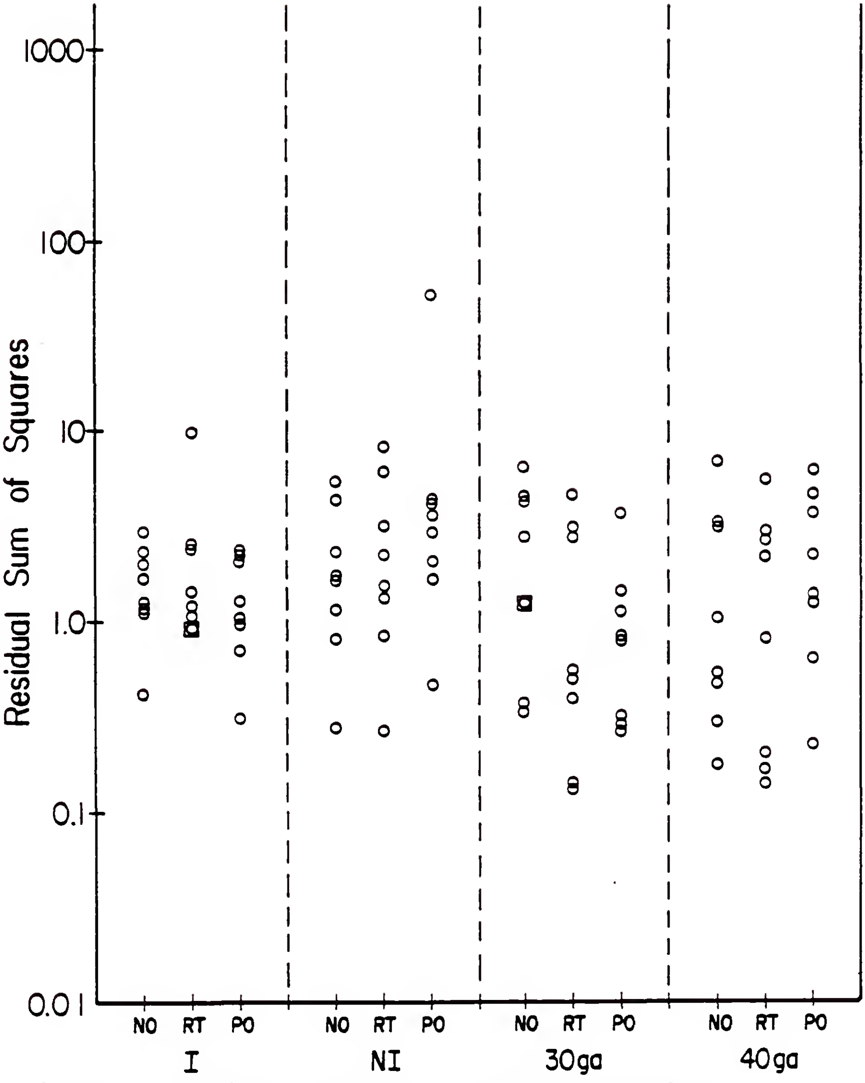


Figure 4-7. Residual sum of squares obtained for cooling. I = Isolated thermocouple; NI = Non-isolated thermocouple; 30ga = 30 gauge wire thermocouple; 40ga = 40 gauge wire thermocouple; NO = No ground; RT = Retort ground method; and PO = Potentiometric ground method. ◘ indicates 2 points at the same residual sum of squares value.

either thermocouple type or ground method. Fig. 4-7 shows that all thermocouple types and grounding methods produced results of the same magnitude and variation. The isolated thermocouple type did appear to have less variation in the residual sum of squares values compared to the other thermocouple types.

The residual sum of squares for cooling were generally higher than those found for heating with the isolated or non-isolated thermocouple, with the exception of the potentiometric grounding method with the non-isolated thermocouple. The length of time necessary to reduce the temperature of the retort to the final cooling retort temperature was the probable cause of the larger sum of squares. The retort temperature dropped rapidly during the first portion of cooling, but the rate of temperature reduction slowed greatly as the retort approached the final cooling retort temperature. Because of this, the polycarbonate slabs were subjected to a changing retort temperature during cooling. One would expect that a changing cooling retort temperature would result in a higher residual sum of squares than a cooling retort temperature that was reached in a few minutes and remained constant throughout the majority of the cooling time.

Fig. 4-8 illustrates cooling data having a sum of squares value of 10.0 which resulted in a cooling curve providing an acceptable estimation of the f_c-value. Unlike the heating curves where the last portion of the curves usually caused problems in f_h-value estimation, the cooling curves demonstrated a gradual bending

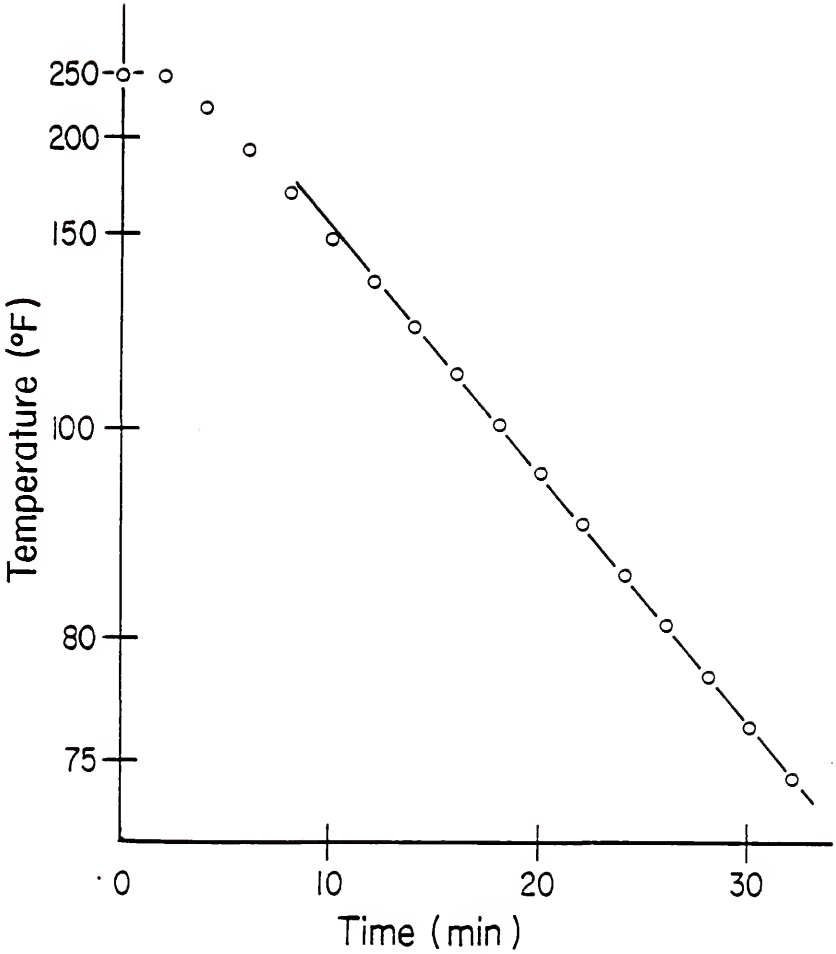


Figure 4-8. Cooling curve with residual sum of squares equal to 10.0.

consistent with the results one would expect with a changing cooling retort temperature. By using a residual sum of squares value of 10.0 as the cut off for an acceptable fit for cooling curves, all cooling curves were acceptable except for one obtained with the non-isolated thermocouple using the potentiometric grounding method with a residual sum of squares of 53.2. This cooling curve can be seen in Fig. 4-9. Cooling, unlike heating, seemed to be nearly independent of the type of thermocouple and grounding method used.

The f_c values (Table 4-4) were all very close to the expected value with the exception of the non-isolated and 40 gauge wire thermocouples where the potentiometric grounding method was used.

Summary And Conclusions

Temperature measurement in retort pouches has been shown to display inaccuracies which arise during heating. These inaccuracies are usually most noticeable in the later stages of heating, but were rarely observed during cooling operations. The errors encountered may be due to the electrical isolation of the pouch from the surrounding heating media or a combination of this electrical isolation and the static electricity characteristics of the pouch material (Pflug, 1975). The problem may also be related to the type of retort used and to the presence of rust or hard water. The vessel of the retort used in this study was made of mild steel and rust was present. The potentiometer used did have common mode noise rejection circuitry; however, Klipec (1967) stated that the rejection circuitry does not totally eliminate the possibility of common mode noise. To minimize

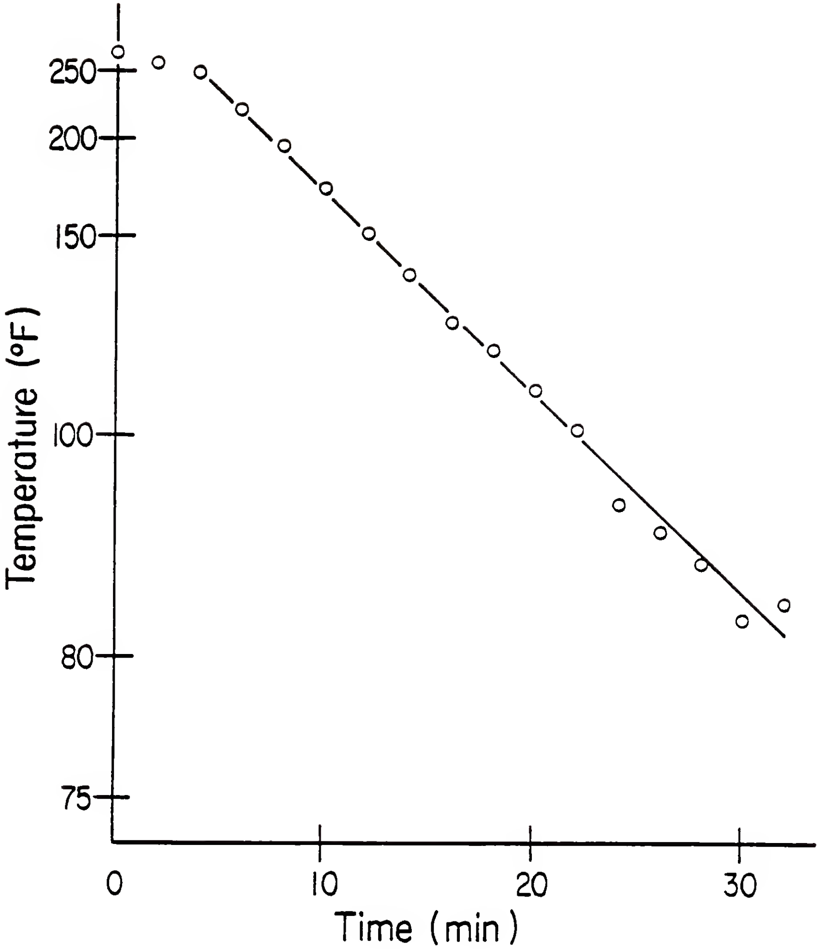


Figure 4-9. Cooling curve with residual sum of squares equal to 53.2.

Table 4-4. Mean f_c-values found for water cooling.

	Grounding Methods[a,b]		
Thermocouple Type	No Ground	Retort Method	Potentiometric Method
Isolated	19.42 ± 0.21^{B}	19.38 ± 0.22^{B}	19.46 ± 0.23^{B}
Non-isolated	19.61 ± 0.29^{B}	19.93 ± 0.57^{B}	21.39 ± 1.27^{A}
30 gauge	19.23 ± 0.30^{B}	19.46 ± 0.24^{B}	19.86 ± 0.67^{B}
40 gauge	19.74 ± 0.57^{B}	19.99 ± 0.97^{B}	21.30 ± 1.46^{A}

[a] Mean f_c-value ± 95% confidence interval.

[b] Means with same letter are not significantly different (Duncan's Multiple Range Test, $p \leq 0.05$).

common mode noise, Klipec suggested shielding the thermocouple wire all the way back to the potentiometer and grounding the shield at the measuring junction of the thermocouple to insure that the shield is at the same potential as the measuring junction. None of the variables in the experiment utilized a shield from the measuring junction all the way back to the potentiometer. The problems observed were probably not due to common mode noise. If they were, since one would expect the same sort of problems with heat penetration tests in cans. This, however, is not the case. Therefore, the problem must be directly associated with the nature or construction of the retort pouch.

The 30 and 40 gauge wire thermocouples did not give adequate results with any of the grounding methods used. Pflug (1975) reported that problems of the nature described in this paper could be solved by running continuous thermocouple wires and a continuous ground wire from the measuring junction of the thermocouple to the ground of the recording potentiometer. This is similar to the retort grounding method used in the present study, since both the recording potentiometer and thermocouple were grounded to the frame of the retort. The major difference was that this study utilized connectors inside the retort vessel. This study did not show the retort grounding method as an acceptable method for wire thermocouples with large retort pouches in the retort system used. Why this discrepancy existed is not known.

From the results presented it is apparent that the best thermocouple choice for retort pouch processing is one with a true electrical shield similar to the isolated thermocouple type. The results obtained from this type of thermocouple were independent of the grounding method and indicated that a cumbersome grounding wire in the retort is not necessary. The electrically shielded thermocouple provided equally good results using no ground or using either of the other two grounding methods. This was an expected result since it is well known that with a true shield the electric intensity inside the shield is zero; thus, the measuring junction of the thermocouple would not be exposed to the stray emf's which the other thermocouple types may have been subjected to.

CHAPTER V
TEMPERATURE SENSOR PLACEMENT IN RETORT POUCHES

Introduction

The establishment of a scheduled process for a low acid food in a retort pouch requires the measurement of temperature at the slowest heating point of the pouch during a number of heat penetration trials. Accurate placement of the temperature measuring device is more difficult in retort pouches than in cans due to the flexible nature of the pouch (Milleville and Badenhop, 1980).

Ball and Olson (1957) concluded that the error experienced in the heating lag factor (j_h) for conduction heating canned foods was not great when the temperature measuring device was displaced from the center; therefore, the effect on process time as calculated by the Ball formula method would also be small. They calculated a 1% error in j_h when temperature was measured 8.3% of the can radius from the center or 4.5% of the can length from the center. These figures were determined from a theoretically derived formula. Measured j_h values were found to agree well with j_h values calculated with the theoretical formula.

Many methods have been proposed for placement of the temperature measuring device in retort pouches. The most common ones include the self-centering strip method (Pflug et al., 1963), the spacer disk or block method (Thorpe and Atherton, 1972), the spring method (Davis et al., 1972), and finally, placement of the temperature measuring device between slices of food or imbedding it in a particulate (Pflug et al., 1963). Each of these methods has been successfully used; however, there has been no investigation of the temperature measuring device placement error that can be tolerated without significantly affecting the process time as determined by heat penetration trials with retort pouches.

The purpose of this investigation was to investigate the sensitivity of the determined process time to the position of temperature measurement in conduction heating low acid foods processed in institutional size retort pouches. This research also examined the error allowed in temperature measurement position that would not significantly affect the determined process time.

Materials and Methods

All analyses were accomplished by means of two computer programs. The programs were numerical solutions of the heat conduction equation for an infinite slab geometry and used a forward direction finite difference technique. One program assumed a finite Biot number (Bi) while the other assumed an infinite Biot number (Bi where the surface heat transfer coefficient is typically large). Listings of the programs can be found in Appendices F and G for the finite and infinite Biot number, respectively. Interior temperatures of points in the infinite slab for both programs were predicted from temperatures of the surrounding positions for the previous time increment according to the following equation (Holman, 1976)

$$T_0^1=M*(T_1^0+T_{-1}^0)+(1-2*M)*T_0^0$$

where $M=(\alpha*\Delta t)/(\Delta x)^2$, the superscripts indicate present (1) or previous (0) time increment, and the subscripts indicate position increments. The temperature of the center position was calculated by assuming the two halves of the infinite slab exhibited symmetrical heat transfer and that there was no heat transfer through the center point. With these assumptions, positions equidistant from the center in opposite halves of the infinite slab would be identical; thus, the center temperature could be calculated with the above formula using the positions adjacent to the center position.

The two programs differed at the surface boundary condition. The infinite Biot number program used a surface boundary condition of

$$T_s=T_m$$

The finite Biot number program used the following equation to evaluate the temperature at the slab surface (Holman, 1976)

$$T_s^1=2*M*((Bi)_{inc}*T_m^0+T_1^0+(1/(2*M)-(Bi)_{inc}-1)*T_s^0)$$

where $(Bi)_{inc}$ is the Biot number calculated using the distance increment rather than the half slab thickness.

Stability criteria for the two programs also differed. The infinite Biot program required $M \leq 0.5$ and the finite Biot program required $M \leq (1/(2*(Bi)_{inc}+2))$ for stability. For the purposes of this experiment, a time increment of 0.01 minut and a distance increment of 1/24 inch were used. These time and distance increments satisfied the stability criteria for both programs for all combinations of the variable levels used.

Both programs were checked for accuracy against the exact solution of the heat conduction equation for the heating of an infinite slab when there was zero come up time. The exact solution program for an infinite slab with an infinite Biot number can be found in Appendix A. The program of the exact solution for an infinite slab with a finite Biot number is listed in Appendix H. Both programs returned results which matched the exact solution within ± 0.1 F with the distance and time increments used in this experiment. The finite Biot number program was also checked against actual data for accuracy. Heat penetration parameters (f_h and j_h), which were calculated with the finite difference program and from the actual data, matched within 4% (Table 5-1).

Two regression models were developed to predict process time of a low acid food in an institutional size retort pouch. Factors affecting heat penetration and, therefore, process time were selected and varied to cover the ranges one normally experiences in processing low acid food products in institutional size retort pouches. Table 5-2 lists these factors and gives the ranges and levels used in the

Table 5-1. Verification of finite difference program accuracy with actual data.

	Actual	Program
f_h	19.83	19.85
j_h 0.14 inches from center	1.04	1.08
j_h 0.26 inches from center	0.81	0.82

Table 5-2. Levels of factors used in regression model development.

Factor	Levels -1	-1/2	0	+1/2	+1	Units
A	0.25	0.375	0.5	0.625	0.75	in
k^*	0.0970	0.1547	0.2124	0.2710	0.3278	BTU/hr ft F
h	10.0	32.5	55.0	77.5	100.0	BTU/hr ft^2 F
T_{ri}	70.0	110.0	150.0	190.0	230.0	F
t_{cu}	1.0	5.75	10.5	15.25	20.0	min
α^*	0.0098	0.0108	0.0117	0.0126	0.0135	in^2/min
$T_{rh}-T_i$	60.0	97.5	135.0	172.5	210.0	F

*Ranges from Uno and Hayakawa (1980)

development of the models. The thermal conductivity and thermal diffusivity ranges were taken from Uno and Hayakawa (1980), who surveyed the available literature and found these ranges to be appropriate for food products. The surface heat transfer coefficient used a range of 10 to 100 BTU/hr ft^2 F. Higher values of the surface heat transfer coefficient could have been used but the small time increment required for stability of the finite difference program would require excessive computer time. Also, the infinite Biot number analysis determined the results one would expect at very high surface heat transfer coefficients. A heating retort temperature of 250 F and a cooling retort temperature of 70 F were used throughout the experiment. At zero time the retort temperature was assumed to be T_{ri}. Temperature increased linearly from that point to the final desired heating retort temperature during the come up time. The cooling retort temperature come down time was assumed to follow an exponential curve as described by Uno and Hayakawa (1980)

$$T=T_{rh}-((T_{rh}-T_{rc})*(t/t_{cd})^{m})$$

The exponent, m, was held constant at 0.1 throughout model development and the come down time was held constant at 10 minutes.

Process time was determined by the heating time, including come up time, required to achieve an F-value of 6.00 minutes for all processes. The process time was determined to ±0.005 minutes.

The statistical design used with the finite Biot number model development was a rotatable central composite design. The 5 levels of the 7 factors included in the design are listed in Table 5-2. The central composite design used a base design of a 1/8 replicate 2^7 factorial (Table 5-3; Cochran and Cox, 1957). Process times for each of the combinations listed in Table 5-3 were determined for the slab center and for each position away from the center up to but not including the surface of the slab. Positions used for determining process time were separated by 1/24 inch. This design was repeated three times for Z-values of 14.0, 18.0, and 22.0 F. These Z-values cover the range expected in microorganisms of concern during processing of low acid foods (Stumbo, 1973).

The infinite Biot number model was also a rotatable central composite design which used a base design of a 1/2 replicate 2^5 factorial (Table 5-4; Cochran and Cox, 1957). The factors k and h were not included in this design since the Biot number was infinite. The positions in each of the slabs and the Z-values analyzed for this model were identical to those in the finite Biot number model.

After all data was collected, regression models were developed to predict process time at any position within the slab. The models were developed using the Statistical Analysis System (Release 82.3, SAS Institute, Cary, NC). A stepwise regression procedure was used which incorporated factors or factor interactions into the model one at a time based on the ability of the factor to improve the regression fit. The number of factors included in the model was determined by matching

Table 5-3. Combinations of factor levels used for rotatable central composite design for the finite Biot number model.

A	k	h	T_{ri}	t_{cu}	α	$T_{rh}-T_i$
-1/2	-1/2	-1/2	-1/2	-1/2	-1/2	-1/2
-1/2	-1/2	-1/2	-1/2	+1/2	+1/2	+1/2
+1/2	+1/2	+1/2	+1/2	-1/2	-1/2	-1/2
+1/2	+1/2	+1/2	+1/2	+1/2	+1/2	+1/2
+1/2	+1/2	-1/2	-1/2	-1/2	-1/2	+1/2
-1/2	-1/2	+1/2	+1/2	-1/2	-1/2	+1/2
+1/2	+1/2	-1/2	-1/2	+1/2	+1/2	-1/2
-1/2	-1/2	+1/2	+1/2	+1/2	+1/2	-1/2
+1/2	-1/2	+1/2	-1/2	-1/2	+1/2	-1/2
-1/2	+1/2	-1/2	+1/2	-1/2	+1/2	-1/2
+1/2	-1/2	+1/2	-1/2	+1/2	-1/2	+1/2
-1/2	+1/2	-1/2	+1/2	+1/2	-1/2	+1/2
+1/2	-1/2	-1/2	+1/2	+1/2	-1/2	-1/2
-1/2	+1/2	+1/2	-1/2	+1/2	-1/2	-1/2
+1/2	-1/2	-1/2	+1/2	-1/2	+1/2	+1/2
-1/2	+1/2	+1/2	-1/2	-1/2	+1/2	+1/2
0	0	0	0	0	0	0
+1	0	0	0	0	0	0
-1	0	0	0	0	0	0
0	+1	0	0	0	0	0
0	-1	0	0	0	0	0
0	0	+1	0	0	0	0

Table 5-3 — continued

A	k	h	T_{ri}	t_{cu}	α	$T_{rh}-T_i$
0	0	-1	0	0	0	0
0	0	0	+1	0	0	0
0	0	0	-1	0	0	0
0	0	0	0	+1	0	0
0	0	0	0	-1	0	0
0	0	0	0	0	+1	0
0	0	0	0	0	-1	0
0	0	0	0	0	0	+1
0	0	0	0	0	0	-1

Table 5-4. Combinations of factor levels used for rotatable central composite design for the infinite Biot number model.

A	T_{ri}	t_{cu}	α	$T_{rh}-T_i$
-1/2	-1/2	-1/2	-1/2	-1/2
+1/2	+1/2	-1/2	-1/2	-1/2
+1/2	-1/2	+1/2	+1/2	+1/2
-1/2	+1/2	+1/2	+1/2	+1/2
+1/2	-1/2	+1/2	-1/2	-1/2
-1/2	+1/2	+1/2	-1/2	-1/2
-1/2	-1/2	-1/2	+1/2	+1/2
+1/2	+1/2	-1/2	+1/2	+1/2
+1/2	-1/2	-1/2	-1/2	+1/2
-1/2	+1/2	-1/2	-1/2	+1/2
-1/2	-1/2	+1/2	+1/2	-1/2
+1/2	+1/2	+1/2	+1/2	-1/2
+1/2	-1/2	-1/2	+1/2	-1/2
-1/2	+1/2	-1/2	+1/2	-1/2
-1/2	-1/2	+1/2	-1/2	+1/2
+1/2	+1/2	+1/2	-1/2	+1/2
0	0	0	0	0
+1	0	0	0	0
-1	0	0	0	0
0	+1	0	0	0
0	-1	0	0	0
0	0	+1	0	0

Table 5-4 — continued

A	T_{ri}	t_{cu}	α	$T_{rh}-T_i$
0	0	-1	0	0
0	0	0	+1	0
0	0	0	-1	0
0	0	0	0	+1
0	0	0	0	-1

the value of the C_p statistic with the regression degrees of freedom plus one for the intercept. The C_p statistic is a measure of the total squared error and allows one to choose the regression model which will minimize bias without increasing the total variance of prediction (Daniel and Wood, 1980). Position was included in the models as a relative position (position/half thickness). During model development with the stepwise procedure, normalization of the data was employed. All variables including process time were normalized by subtracting the overall mean of that variable and dividing by the standard deviation of that variable's values. After the models were developed, the models were transformed back to actual values of all variables.

Results and Discussion

Statistical Model

The models obtained for prediction of process time at any position in an infinite slab can be found in Tables 5-5 and 5-6 for finite and infinite Biot numbers, respectively. The models resulted in R-squared values of 0.975 and 0.980 for the finite and infinite Biot number models, respectively. Even though the models fit the data well, caution should be used in predicting process times from the models since examination of the residuals revealed that errors of ±5 minutes were not uncommon when using the models to predict process time at the extremes of the design. The purpose of developing the models was not to predict process time but rather to identify the

Table 5-5. Model for process time prediction at any position in a slab with a finite Biot number.

Factor	Coefficient
Intercept	-59.6
Pos	25.3
A	132
k	70.0
h	-0.552
T_{ri}	0.0630
t_{cu}	0.0894
α	7600
$(T_{rh}-T_i)$	0.425
Z	-1.11
Pos*Pos	-26.5
Pos*A	-50.7
Pos*k	8.27
Pos*h	-0.0416
Pos*α	1110
A*A	30.3
k*k	-113
h*h	0.00394
T_{ri}*T_{ri}	-0.000296
t_{cu}*t_{cu}	-0.0110
α*α	-264000
$(T_{rh}-T_i)$*$(T_{rh}-T_i)$	-0.000375

Table 5-5 — continued

Factor	Coefficient
Z*Z	-0.0196
A*Z	-2.30
h*Z	0.00370
α*Z	59.0
h*(T_{rh}-T_i)	-0.000654
A*α	-4550
A*(T_{rh}-T_i)	0.296
T_{ri}*t_{cu}	111
t_{cu}*(T_{rh}-T_i)	-0.00340
α*(T_{rh}-T_i)	-29.5

Table 5-6. Model for process time prediction at any position in a slab with an infinite Biot number.

Factor	Coefficient
Intercept	35.1
Pos	26.2
A	121
T_{ri}	-0.0183
t_{cu}	1.14
α	-5520
$(T_{rh}-T_i)$	-0.0751
Z	-0.731
Pos*Pos	-33.6
Pos*A	-57.2
Pos*α	1370
Pos*Z	0.161
A*A	65.8
A*T_{ri}	-0.0285
A*t_{cu}	-0.459
A*α	6050
A*$(T_{rh}-T_i)$	0.234
A*Z	-2.06
T_{ri}*t_{cu}	-0.00207
T_{ri}*$(T_{rh}-T_i)$	0.000146
t_{cu}*t_{cu}	0.010
t_{cu}*$(T_{rh}-T_i)$	-0.00211

Table 5-6 -- continued

Factor	Coefficient
$\alpha * \alpha$	227000
$\alpha * Z$	48.9
$Z * Z$	0.0164

factors which interacted with thermocouple position during a heat penetration trial.

From Table 5-5 it can be concluded that the sensitivity of thermocouple position on process time was dependent on the Biot number, since position exhibited a significant interaction with thickness, k, and h-value. Fig. 5-1 exhibits the effect of Biot number on process time at different positions in a relative form (process time/process time at center; position/half slab thickness). All factors in Fig. 5-1 were at the midpoint of the design except the h-value which was varied to obtain different Biot numbers. As the Biot number was increased to infinity, temperature sensor positioning became more critical. This was expected, since at the low Biot numbers the resistance to heat transfer was greater at the surface of the slab than in the slab. This would result in a more uniform temperature distribution in the slab. Thus, the F-value received by different points in the slab would not vary as much as with a high Biot number. In all cases no measurable decrease in process time was found before the process was determined 1/4 of the total half slab thickness away from the center point. In the case of the one inch slab illustrated, a placement error of ±1/8 inch would result in no error in process time determination for any Biot number. The interaction between temperature measurement position and Biot number became important in process time determination when the temperature measurement device was located near the surface of the slab. It was of little significance near the center of the slab.

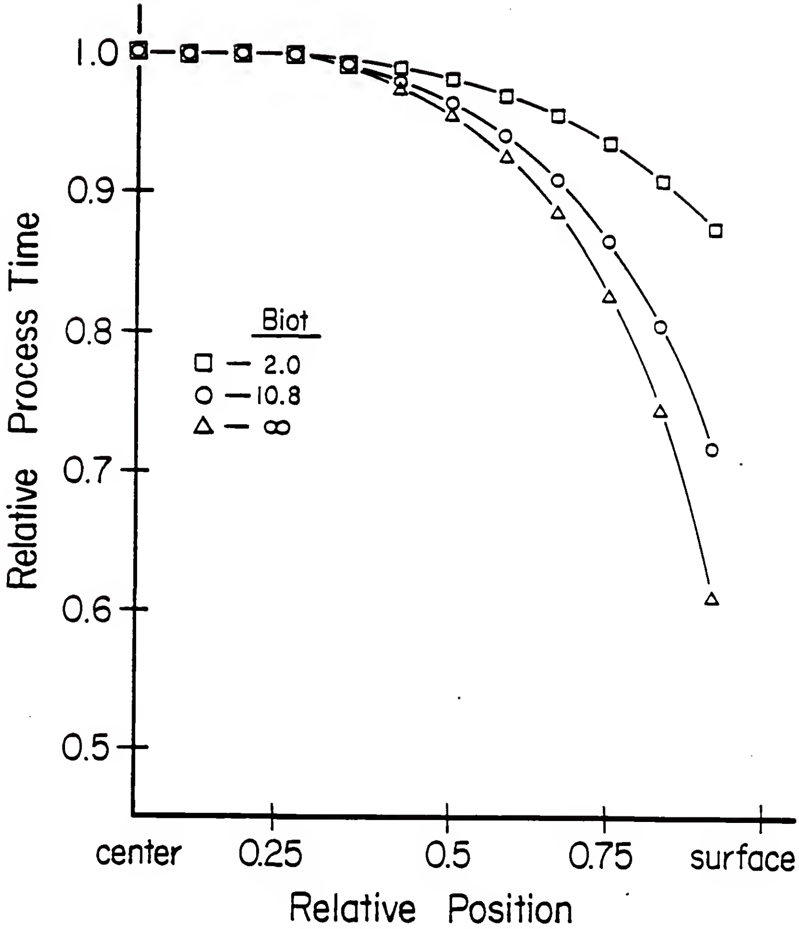


Figure 5-1. Interaction of Biot number with position on relative process time. All factors at midpoint of design except h-value which was varied to obtain different Biot numbers.

The half slab thickness also significantly interacted with the position of temperature measurement. Fig. 5-2 illustrates the effect of half slab thickness on process time at equal Biot numbers. To obtain this data the h-value was varied to maintain a constant Biot number at the different thicknesses, while all other factors were kept at the design midpoint. The positioning of the temperature measuring device was found to be more critical as half slab thickness increased. The practical interpretation of this position and thickness interaction is not straightforward. The thicker slab was more sensitive to relative position of the temperature measuring device; however, the thicker slab allowed a larger actual placement error without significantly affecting the determined process time. This is due to the larger temperature gradient that would be found in a thicker slab.

Thermal diffusivity interacted with temperature measurement position in both the finite and infinite Biot number models (Fig. 5-3). In this situation all factors were at the midpoint of the finite Biot design with the exception of thermal diffusivity. The interactions of thermal diffusivity and position were small compared to the interaction of position with Biot number and slab half thickness. Also, the interaction of position and Z-value, which appeared in the infinite Biot number model, was also small.

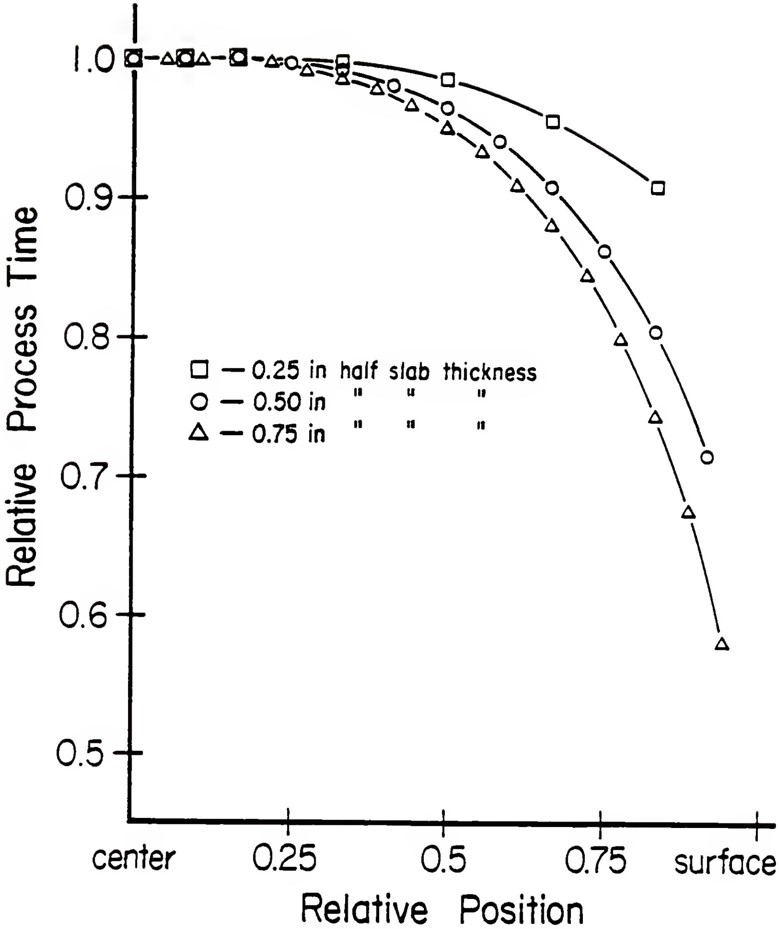


Figure 5-2. Interaction of half slab thickness with position on relative process time. Curves are at equal Biot numbers (10.8), all other factors are at the design midpoint.

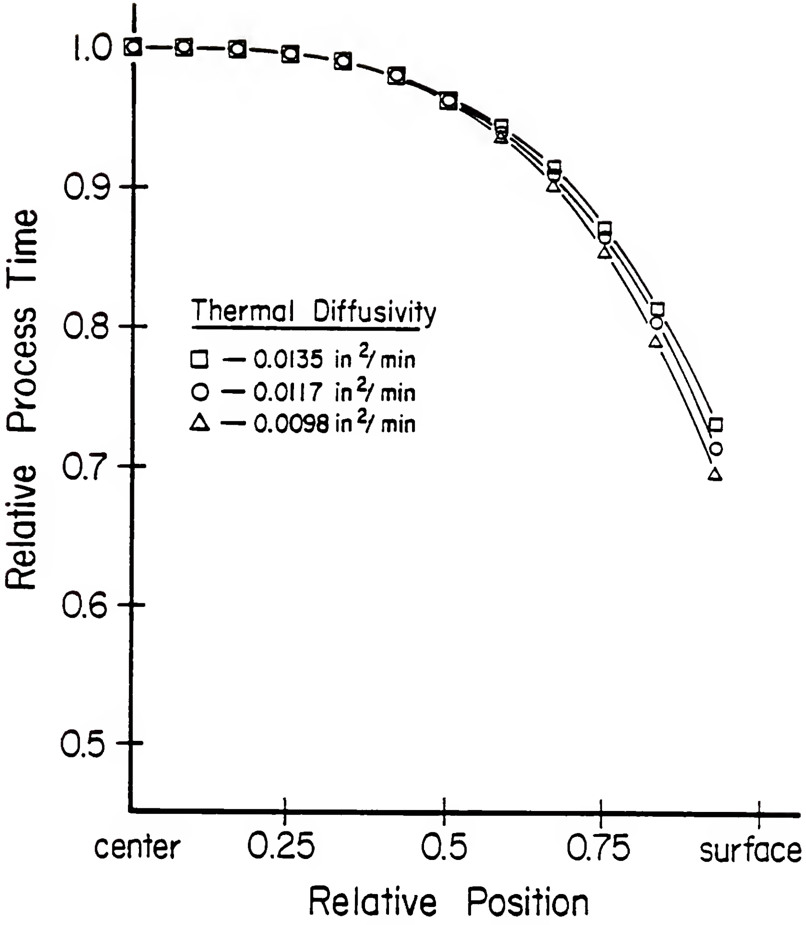


Figure 5-3. Interaction of thermal diffusivity with position on relative process time. All other factors are at the design midpoint.

Worst Case Situation

Graphs showing relative process time versus relative position such as Fig. 5-1 through 5-3 are convenient for illustrating the interactions that occur with various factors and position of the temperature measuring device; however, they are not as valuable for practical interpretation of the data. Actual process times determined at various positions in the slab and the F-value received by the center of the slab would be a better method of determining the importance of position of temperature measurement in retort pouch processing. Levels of the factors used in the statistical model were set at the extreme values which would result in the greatest sensitivity of determined process time to temperature measurement position. The values of the factors that resulted in the worst case situation were: infinite Biot number, high Z-value, low initial retort temperature, short come up time, low thermal diffusivity, and a large temperature differential between retort and initial product temperature (Table 5-2). Fig. 5-4 shows the data generated by the infinite Biot number program for this worst case situation for the 0.75 and 0.25 inch half slab thickness. Fig. 5-4 illustrates the effect of the location of the temperature measuring device on the process time as determined by the improved general method. For both half slab thicknesses there was a region around the center in which the process time was not greatly affected by temperature sensor position.

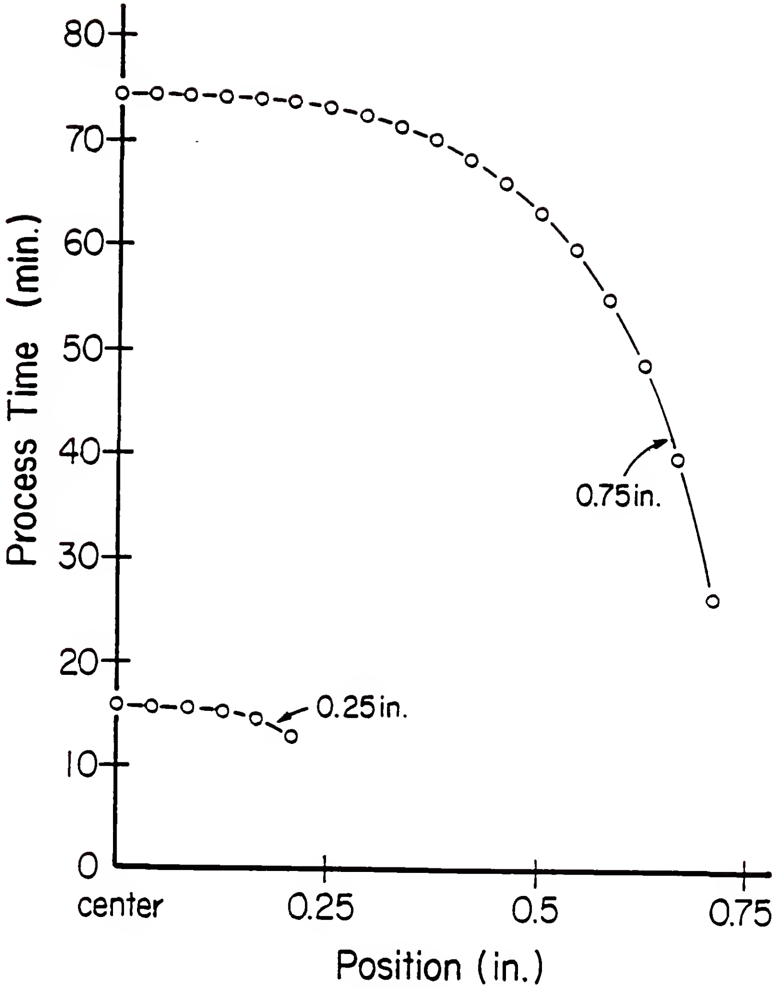


Figure 5-4. Actual process time versus actual position for 0.75 and 0.25 inch half slab thicknesses. Extreme factor levels were used to achieve maximum sensitivity of determined process time to position of temperature measurement.

The F-value received by the center point of the slab if the process was determined with a displaced temperature sensor would be less than the desired F-value at the center. Fig. 5-5 illustrates the effect of position of the temperature measuring device on the F-value received by the center of the slab for this worst case situation. If one were to allow an error in the center F-value of 0.5 minute, the temperature measurement device could be offset from the center by ±0.125 inch for the 0.25 inch half slab thickness and ±0.25 inch for the 0.75 inch half slab thickness. If an error of only 0.1 minute in the center F-value was acceptable, the temperature measuring device could be displaced from the center ±0.083 inch for the 0.25 inch half slab thickness and ± 0.167 inch for the 0.75 inch half slab thickness.

A common safety factor used when determining thermal processes for low acid food products is the rounding of the calculated process time up to the next full minute. Fig. 5-6 graphically depicts the displacement of the temperature measuring device from the slab center which resulted in a one minute reduction in determined process time for different slab half thicknesses. A slab with a half thickness of 0.25 inch experienced a one minute drop in determined process time at 0.17 inch away from the center while a 0.75 inch slab did not experience a one minute drop in determined process time until the temperature measuring device was 0.25 inch away from the center. Even though the thinner slabs were less sensitive to relative position, the amount of displacement of the temperature measuring device away from the center which could be tolerated without seriously affecting determined process time was less than that for thicker slabs.

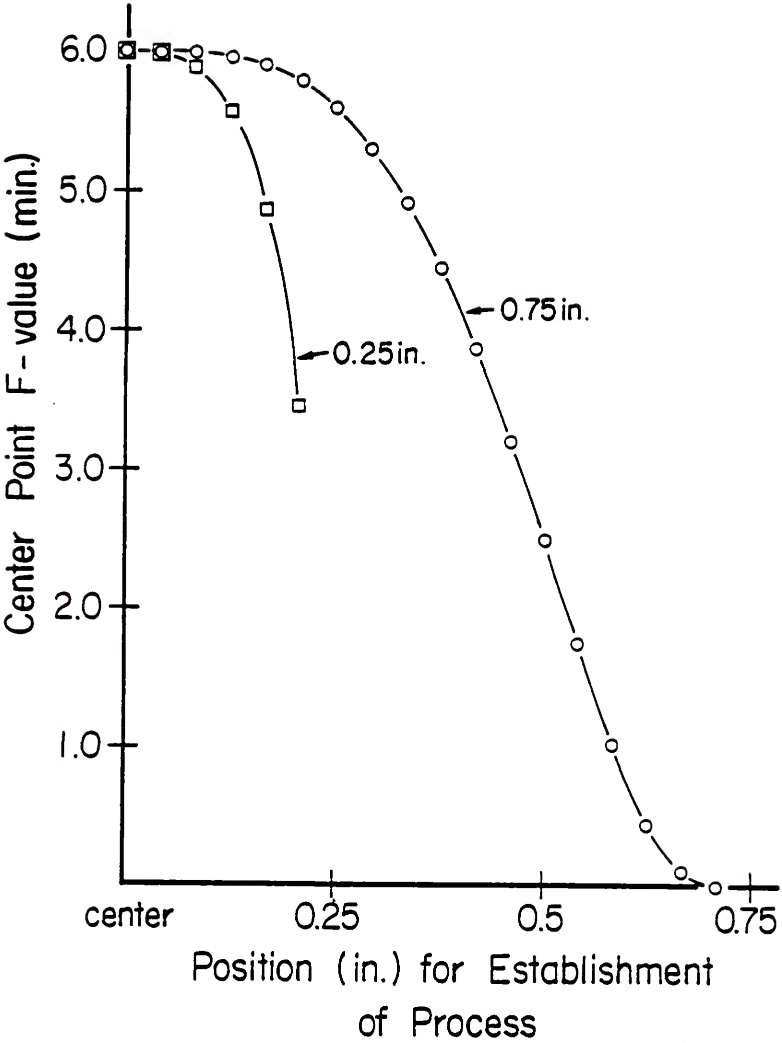


Figure 5-5. Center point F-value found when process was based on temperature measurement at different positions in 0.75 and 0.25 inch half slab thicknesses. Extreme factor levels were used to achieve maximum sensitivity of determined process time to position of temperature measurement.

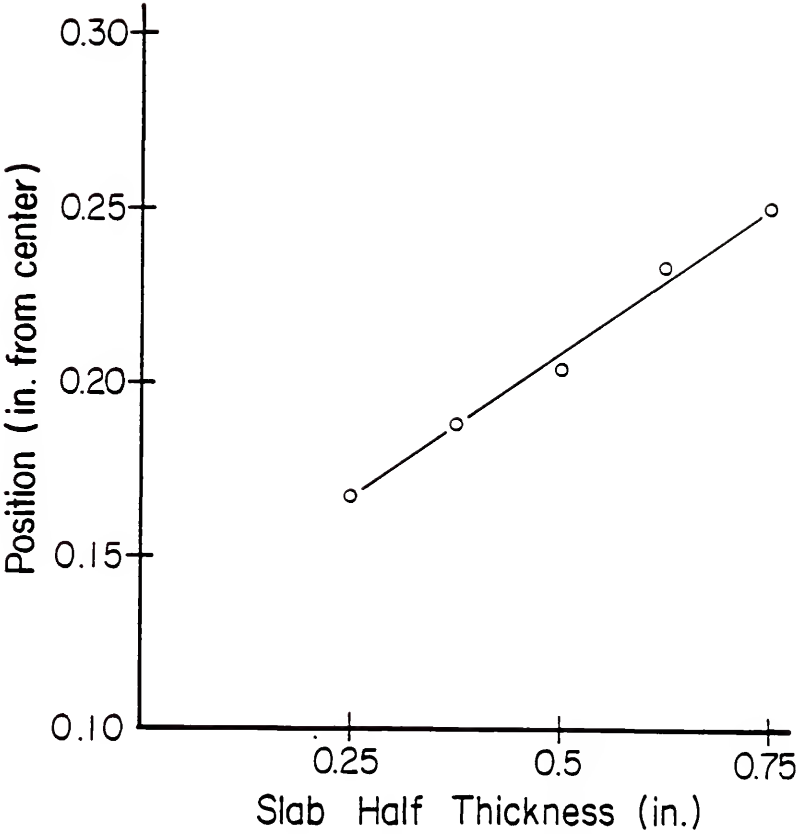


Figure 5-6. Position where 1.0 minute drop in determined process time occurred as a function of slab half thickness.

Summary and Conclusions

Models for the prediction of process time required to obtain an F-value of 6.0 were presented for processing conditions with an infinite or finite Biot number. These models were used to evaluate the effect of processing and product variables on the sensitivity of determined process time to position of the temperature measuring device. Through analysis of the models, a worst case situation was analyzed in which the factors were set at the extreme levels which would result in the greatest effect of the temperature sensor position on the determined process time. This worst case situation revealed that position of the temperature measuring device was not critical within a small range of positions around the center of the slab; however, placement rapidly became a very important factor outside of this small range around the slab center as illustrated in Fig. 5-4 and 5-5.

Even though thicker slabs were shown to be more sensitive to relative position of the temperature measuring device, the actual positioning error allowed without significantly affecting the determined process time was greater than that for thinner slabs. Therefore, retail size retort pouches (less than 1 lb capacity) would be subject to a greater error in determined process time than the thicker institutional size retort pouches, due to positioning errors of the temperature measuring device.

When institutional size retort pouches having thicknesses above 1/2 inch are used, the temperature measuring device should be located within ±1/8 inch of the pouch center to avoid errors in process time determinations. As pouch thickness increases, this becomes a conservative estimate. This allowed error in temperature measurement position could be used for evaluation of positioning methods currently in use for retort pouches and as a standard for new methods. Any of the methods commonly used to locate temperature measuring devices in retort pouches should give sufficient placement accuracy if used properly. There is one method, however, that could cause greater positioning problems than other methods. In this method the temperature measuring device is placed between slices of food such as meat or fish fillets with no other means of support. One could expect a large variation in the position of the temperature measuring device with this method. Another concern would be pouches containing a large amount of air, especially if they were not properly confined. Movement of the effective center or cold spot as discussed in a previous chapter could be great if swelling of the pouch was not restricted during processing. This cold spot movement would be analagous to displacement of the temperature measurement device away from the center of the pouch and would result in the same type of effect that has been illustrated in this research.

CHAPTER VI
SUMMARY AND CONCLUSIONS

This study examined variables in the thermal processing of institutional size retort pouches which could affect either the accuracy of heat penetration data or the rate of heat penetration into a pouched food. Two variables examined which could affect the accuracy of heat penetration data were thermocouple grounding methods and temperature sensor placement effects on the determined process time. Variables examined which affected the rate of heat penetration included flow rate of the heating medium, design of the racking system, the presence of retort pouch material, and the effect of entrapped air.

All the variables examined were placed in order of their importance for the processing of institutional size retort pouches

1. Temperature measurement errors
2. Entrapped air
3. Rack design
4. Flow rate
5. Temperature sensor placement
6. Presence of pouch material

Temperature measurement errors were selected as the most important factor. Accurate temperature measurement during heat penetration trials is a necessity. Without accurate temperature measurement, one cannot rely on the gathered data; therefore, any conclusions drawn from the data may not be accurate. This research demonstrated that of all the methods tested, the electrically isolated thermocouples gave the most consistant and accurate results. The non-isolated thermocouple gave acceptable results with the retort ground method and no ground; however, the results were not as consistent as with the isolated thermocouple. The isolated thermocouple also was independent of grounding method, thereby eliminating the need for a cumbersome ground wire. Failure to address this potential problem in retort pouches may lead to serious miscalculations of process times.

Entrapped air was shown to seriously retard the rate of heat penetration in retort pouches. A 10 X 9 X 1.5 inch retort pouch with 25 ml of air present showed a 46% reduction in the calculated center point F_o-value compared to the same size pouch with only 5 ml of air present. The best solution to the problem of entrapped air would be to simply avoid the presence of entrapped air. Large unknown quantities of entrapped air in a horizontally processed retort pouch could represent a potential health hazard.

If air or any noncondensible gas is present in a retort pouch, the maximum expansion allowed by the confining rack design can play an important role in the rate of heat transfer. In general, the greater the expansion allowed by the rack design, the slower the rate of heat transfer.

In addition to showing the relationship of rack design to entrapped air, this research showed that a perforated rack design should be used. The size of the perforations tested in this research did not greatly affect the rate of heat transfer. The solid rack design showed a large decrease in the rate of heat transfer which was probably due to the lack of intimate contact between the polycarbonate slabs and the top and bottom of the rack. If a solid rack is to be used, one should insure that the retort pouch is in intimate contact with the rack.

Flow rate of the heating medium, although not studied directly in this research, can affect the rate of heat transfer into retort pouches. This is especially true at low Reynolds numbers. However, high flow rates such as the Reynolds number of 32,000 for flowing water, resulted in a heat transfer rate indistinguishable from that of 100% steam.

The placement of the temperature measuring device in a retort pouch for a heat penetration trial should not present problems for the food processor. A placement error of ±1/8 inch from the center or cold spot of a 1/2 inch thick pouch was found to have a minimal effect on the determined process time. As pouch thickness increased, a greater placement error could be allowed without significantly affecting the determined process time. Any of the available methods for the location of the temperature sensor in a retort pouch should be able to give the required accuracy if used correctly.

Movement of the cold spot upward, which was shown to occur when air was entrapped in the pouch, would have the same effect as displacing the temperature sensor from the center of the pouch. However, the reduction of heat transfer due to the entrapped air would tend to overshadow the relatively small effect of cold spot migration.

The presence of pouch material was found to have essentially no effect on the rate of heat penetration into retort pouches. The effect of pouch material would only be of concern if the pouch material in question was much thicker than the standard material used in this study.

All the factors studied, with the exception of the effect of pouch material, were shown to be capable of seriously affecting a retort pouch process. In a retort pouch processing system, all these factors should be examined to insure the consistent production of a safe, high quality product.

APPENDIX A

PROGRAM FOR INFINITE SLAB EXACT SOLUTION, INFINITE BIOT NUMBER

```
C  This program calculates the temperature at a specific point
C    in an infinite slab for a specified number of time
C    increments through use of the exact mathematical solution
C    of the heat conduction equation found in Carslaw and
C    Jaeger (1959).  An infinite Biot number is assumed.
C
C  VARIABLES
C
C    ALPHA     Thermal diffusivity (in**2/min)
C    LEN       Half slab thickness (in)
C    T         Temperature calculated at current TIME (F)
C    TI        Initial slab temperature (F)
C    TIME      Current time for calculation of T (min)
C    TIMINC    Time increment (min)
C    TIMTOT    Last TIME value for temperature calculation (min)
C    X         Position in slab for calculation (Center = 0.0, in)
C
C
      REAL LEN
      OPEN(UNIT=5,FILE='EXTSLB.DAT',STATUS='OLD',
     C  RECORDTYPE='VARIABLE')
      OPEN(UNIT=6,FILE='EXTSLB.RES',STATUS='NEW')
      PI=3.141593
      SUM=0.0
 5    READ(5,*,END=60)RT,TI,ALPHA,LEN,X,TIMINC,TIMTOT
      TIME=TIMINC
      WRITE(6,15)RT,TI,ALPHA,LEN,X
15    FORMAT('1RETORT TEMP = ',F5.1/' INITIAL TEMP = ',F5.1,
     C  /,' THERMAL DIFFUS = ',F6.4,' IN**2/MIN'/
     C ' HALF SLAB THICKNESS = ',F4.2,' IN'/' X = ',F5.3,' IN')
      WRITE(6,20)
20    FORMAT('0',5X,'TIME (MIN)',3X,'TEMP (F)'/6X,'----------',
     C  3X,'--------')
C
C  Calculate temperature at TIME
C
40    T=(1.-4.*SLBSUM(TIME,ALPHA,LEN,X)/PI)*(RT-TI)+TI
      WRITE(6,50)TIME,T
50    FORMAT(9X,F6.2,6X,F5.1)
C
C  Check to see if total time has been exceeded
C
      IF(TIME.GT.TIMTOT)GOTO5
      TIME=TIME+TIMINC
      GOTO40
60    STOP
      END
C
C
      FUNCTION SLBSUM(TIME,ALPHA,LEN,X)
C  This function calculates the infinite sum associated
C    with the exact solution of an infinite slab with an
C    infinite Biot number (Carslaw and Jaeger, 1959).
C
C  VARIABLES
C    TIME     Time of calculation
C    ALPHA    Thermal diffusivity
C    LEN      Half thickness of slab
C    X        Position in slab (center = 0.0)
C
C
      DOUBLE PRECISION PI,SUM,AEX,A
      REAL LEN
      PI=3.141592653589793
      SUM=0.
      DO 10 I=1,80
      N=I-1
      AEX=DBLE(ALPHA)*(2*N+1.)**2*PI**2*DBLE(TIME)
     C  /(4*DBLE(LEN)**2)
      IF((AEX.GE.50.).AND.(N.GE.1))GOTO20
      A=((-1.)**N/(2.*N+1.))*DCOS((2.*N+1.)*PI*DBLE(X)/
     C  (2.*DBLE(LEN)))/DEXP(AEX)
      SUM=SUM+A
10    CONTINUE
20    SLBSUM=SNGL(SUM)
      RETURN
      END
```

APPENDIX B

PROGRAM FOR RECTANGULAR PARALLELEPIPED EXACT SOLUTION INFINITE BIOT NUMBER

```
C  This program calculates the temperature at a specific
C    point in a parallelpiped for a series of times through
C    use of the exact mathematical solution of the heat
C    conduction equation found in Carslaw and Jaeger (1959).
C    An infinite Biot number is assumed.
C
C  VARIABLES
C    RT          Retort temp (F)
C    TI          Initial temp (F)
C    TIMINC      Time increment (min)
C    TIMTOT      Total process (heating) time (min)
C    TIMST       Time for initial calculation
C    ALPHA       Thermal diffusivity (in**2/min)
C    A,B,C       Half dimensions of the pouch (in.)
C    X,Y,Z       Coordinates of interest (geometric center= 0,0,0):
C                  X must be matched with A, Y with B, and Z with C
C    TEMP        Calculated temperature for a specific time
C    TIME        Time of temperature calculation
C    T( )        Array holding temp values for specific time
C    TIM( )      Array holding time
C    KOUNT       Counter indication last address filled in T & TIM
C                  arrays
C
      DIMENSION T(50),TIM(50)
      OPEN(UNIT=5,FILE='EXTREC.DAT',STATUS='OLD',
     C   RECORDTYPE='VARIABLE')
      OPEN(UNIT=6,FILE='EXTREC.RES',STATUS='NEW')
      PI=3.141593
5     READ(5,*,END=130)A,B,C,X,Y,Z
      READ(5,*)TIMINC,TIMTOT,RT,TI,ALPHA,TIMST
      TIME=TIMST
      KOUNT=1
C
C   Next lines calculate temp at a specific time
C
18    TEMP=TI+(RT-TI)*(1.-64.*SLBSUM(TIME,ALPHA,A,X)*
     C  SLBSUM(TIME,ALPHA,B,Y)*SLBSUM(TIME,ALPHA,C,Z)/PI**3)
30    T(KOUNT)=TEMP
      TIM(KOUNT)=TIME
C
C   Check to see if alloted time has passed
C
```

```
      IF(TIME.GE.TIMTOT)GOTO110
C
C   Increase counter and time value, and go back and calc temp for
C     new time
C
      KOUNT=KOUNT+1
      TIME=TIME+TIMINC
      GOTO18
C
C   Output
C
110   WRITE(6,120)A,B,C,X,Y,Z,ALPHA,RT,TI
120   FORMAT('1POUCH SIZE   ',F5.2,' X ',F5.2,' X ',F5.2,' INCHES'/
     C  ' COORDINATES  ',F5.2,2(' X ',F5.2),' INCHES'/
     C  ' DIFFUSIVITY  ',F6.4,' IN**2/MIN'/' RETORT TEMP  ',F5.1,
     C  ' F'/' INITIAL TEMP ',F5.1,' F'
     C  ///3X,'TIME (MIN)',
     C  '  TEMP (F)'/3X,'----------  --------')
      DO 127 JJJ=1,KOUNT
      WRITE(6,123)TIM(JJJ),T(JJJ)
123   FORMAT(5X,F5.1,7X,F5.1)
127   CONTINUE
C
C   Read another set of data
C
      GOTO5
130   STOP
      END
C
C
      FUNCTION SLBSUM(TIME,ALPHA,LEN,X)
C
C  This function calculates the infinite sum associated
C    with the exact solution of an infinite slab with an
C    infinite Biot number (Carslaw and Jaeger, 1959).
C
C  VARIABLES
C    TIME     Time of calculation
C    ALPHA    Thermal diffusivity
C    LEN      Half thickness of slab
C    X        Position in slab (center = 0.0)
C
C
      DOUBLE PRECISION PI,SUM,AEX,A
      REAL LEN
      PI=3.141592653589793
      SUM=0.
      DO 10 I=1,80
      N=I-1
      AEX=DBLE(ALPHA)*(2*N+1.)**2*PI**2*DBLE(TIME)
     C  /(4*DBLE(LEN)**2)
      IF((AEX.GE.50.).AND.(N.GE.1))GOTO20
      A=((-1.)**N/(2.*N+1.))*DCOS((2.*N+1.)*PI*DBLE(X)/
     C  (2.*DBLE(LEN)))/DEXP(AEX)
      SUM=SUM+A
10    CONTINUE
20    SLBSUM=SNGL(SUM)
      RETURN
      END
```

APPENDIX C
PROGRAM TO CALCULATE HEAT PENETRATION PARAMETERS

```
C  This program was written to calculate heat penetration
C  parameters for both straight line and broken heating curves.
C  The program will analyze up to 50 sets of heating and cooling
C  times and temperatures.  Each set may have up to 50 time-
C  temperature pairs.  A minimum of 6 pairs are needed before the
C  program will determine the parameters.
C
C  Heating data can be analyzed or heating and cooling data can be
C  analyzed together; no provision has been made for the analysis
C  of cooling data alone.  A number of input options are available
C  and are controlled by KONT.  If heating times are to be generated,
C  TIMST must be entered and must correspond to the first
C  temperature entered.  TIMINT must also be entered and must
C  correspond to the time interval separating each of the
C  temperature observations.  If heating times are to be entered
C  manually, TIMST and TIMINT need not be included in the input.
C  TIMSTC and TIMINTC have identical functions in regard to the
C  generation of cooling times.
C
C  Times and temperatures should begin near the end of the heating
C  or cooling cycle and need to be entered with decreasing time.
C
C  Heat penetration parameters are calculated according to Stumbo
C  (1973).  The straight line portion of the heating or cooling
C  curves is accomplished by taking the first five sets of time-
C  temperature data and calculating a line by least squares linear
C  regression.  This line is projected to the next time interval
C  and the calculated temperature is compared with the measured
C  temperature.  If the two temperatures differ by DEGDEV or more,
C  that time-temperature pair is not included in the regression
C  calculation and the program proceeds to the next pair.  This
C  new pair is then tested against DEGDEV; if it is acceptable it
C  will be included in the regression calculation.  The program will
C  continue until it has found 6 consecutive time-temperature pairs
C  that do not meet the DEGDEV criteria specified, or until the end
C  of the data set is reached.  When a broken heating curve is
C  encountered, the program will take the first 5 pairs after the
C  6 pairs rejected from the first Fh calculation (FH2), calculate
C  a regression line and proceed in the manner explained above.
C  The program recognizes a broken heating curve if TPIH is greater
C  than 200 F, or if JH is less than 0.5.
C
```

```
C  Two sets of output are obtained for each computer run.  The first
C  is a table of the heat penetration paramters and the second is a
C  single line of data suitable for inclusion into a data file of
C  heat penetration results.
C
C  INPUT AND OUTPUT VARIABLES
C
C    COMUP      Time (min) for retort to reach processing temperature
C    CRT        Cooling retort temperature (F)
C    CTI        Initial product temperature for cooling (F)
C    DEGDEV(X)  Maximum difference allowed between input temperature
C                 and projected temperature (F)
C                     X=1 for heating
C                     X=2 for cooling
C    FC         Time for the straight line portion of a cooling curve
C                 to transverse one log cycle (min)
C    FH1        Time for the straight line portion of a heating curve
C                 to transverse one log cycle (min)
C    FH2        For a broken heating curve.  Time for the second
C                 straight line portion of the heating curve to
C                 transverse one log cycle
C    FHMIN1     Number of minutes used to determine regression line
C                 for FH1
C    FHMIN2     Number of minutes used to determine regression line
C                 for FH2
C    GBH        Temperature at which the two straight line portions of
C                 a broken heating curve intersect
C    JC         Lag factor for cooling curve
C    JH1        Lag factor for heating curve.  For broken heating
C                 curve only the JH of the first straight line portion
C                 is reported.
C    JCMIN      Number of minutes used to determine regression line
C                 for FC
C    KONT       Control card:  1 - Heating only, generate time
C                              2 - Heating and cooling, generate
C                                    heating time, read cooling time
C                              3 - Heating only, read time
C                              4 - Heating and cooling, read heating
C                                    and cooling time
C                              5 - Heating and cooling, generate
C                                    heating and cooling time
C    KNUM(X)    Number of time-temperature values
C                 X=1 heating
C                 X=1 cooling
C    RT         Heating retort temperature (F)
C    TEMP(X, )  Array containing input temperatures
C                 X=1 heating
C                 X=2 cooling
C    TI         Initial product temperature before heating (F)
C    TIME(X, )  Array containing input times (min)
C                 X=1 heating
C                 X=2 cooling
```

```
C    TIMINT     Time (sec) between each heating temperature entered.
C                 Only necessary of KONT = 1, 2, or 5
C    TIMINTC    Time (sec) between each cooling temperature entered.
C                 Only necessary of KONT = 5
C    TIMST      Time (min) of first heating temperature entered.  Only
C                 necessary if KONT = 1, 2, or 5
C    TIMSTC     Time (min) of first cooling temperature entered.  Only
C                 necessary if KONT = 5
C
C  All other variables for input and output are for data cataloging.
C
C
       INTEGER PAGE,DEGDEV(2),FINISH,POSS
       REAL JH1,JH2,JCMIN,JC
       DIMENSION TEMP(2,50),TIME(2,50),KNUM(2),TEMP1(2,50),TIME1(2,50)
       OPEN(UNIT=5,FILE='FH2FC.DAT',FORM='FORMATTED',RECL=80,
      C  STATUS='OLD')
       OPEN (UNIT=1, FILE='NB4.DAT', FORM='FORMATTED', RECL=80,
      C  STATUS='NEW')
       OPEN (UNIT=2, FILE='DATAOUT.FH2', FORM='FORMATTED',
      C  RECL=80, STATUS='NEW')
       WRITE(2,10)
10     FORMAT('OPAGE KT',T16,'JH1',3X,'FH1',2X,'FHMIN1',3X,
      C  'JH2',3X,'FH2',2X,'FHMIN2',2X,'GBH',4X,'FC',5X,'JC',
      C  2X,'JCMIN'/' ---- --',T15,'----  ----- ',
      C  '-----  ----  ----- ------ -----  -----  ---- -----')
       DO 200 II=1,50
       READ(5,20,END=900)KONT,KTRIAL,CRT,CTI,TIMSTC,TMINTC
20     FORMAT(I2,I3,3F5.1,F5.0)
       READ(5,30)PAGE,KREP,KDUM1,KDUM2,KDUM3,
      C   RT,TI,COMUP,KNUM(1),KNUM(2),DEGDEV(1),
      C   DEGDEV(2),TIMST,TIMINT,TCVERT,TCHORZ,FRATE,
      C   AIRPSI,KSORT1,KSORT2,KSORT3
30     FORMAT(I3,2I2,2I3,2F5.1,F5.2,2I2,2I1,F5.1,F5.0,2F5.3,2F5.1,
      C   3I2)
       JJ=KNUM(1)
       JK=KNUM(2)
C
C  Read number of heating temperatures specified by KNUM(1)
C
       READ(5,40)(TEMP(1,I),I=1,JJ)
40     FORMAT(16F5.1)
       IF(KONT.EQ.3)GOTO60
       IF(KONT.EQ.4)GOTO60
C
C  Generate heating time array for KONT=1,2, or 5
C
       TIME(1,1)=TIMST
       TIMINT=TIMINT/60
       DO 50 I=2,JJ
       TIME(1,I)=TIME(1,I-1)-TIMINT
50     CONTINUE
```

```
      IF(KONT.EQ.2)GOTO80
      IF(KONT.EQ.5)GOTO85
      KM=1
      GOTO90
C
C  Read heating time for KONT=3 or 4
C
60    READ(5,70)(TIME(1,I),I=1,JJ)
70    FORMAT(16F5.2)
      IF(KONT.EQ.4)GOTO80
      KM=1
      GOTO90
C
C  Read cooling temperatures and times for KONT=2 or 4
C
80    KM=2
      READ(5,40)(TEMP(2,I),I=1,JK)
      READ(5,70)(TIME(2,I),I=1,JK)
      GOTO90
C
C  Read cooling temperatures and generate cooling times for KONT=5
C
85    KM=2
      READ(5,40)(TEMP(2,I),I=1,JK)
      TIME(2,1)=TIMSTC
      TMINTC=TMINTC/60.
      DO 87 I=2,JK
      TIME(2,I)=TIME(2,I-1)-TMINTC
87    CONTINUE
C
C  Calculate heat penetration parameters for heating
C
90    CALL CALC(1,JJ,DEGDEV(1),RT,CRT,TI,CTI,TIME,TEMP,COMUP,
     C  FH2,JH2,FHMIN2,INSUF1,JC,JCMIN,FINISH,B02,B12,FC)
      IF(INSUF1.EQ.1)POSS=1
      IF(INSUF1.EQ.1)GOTO110
C
C  Determine if a broken heating curve was encountered
C
      TPIH=RT-(JH2*(RT-TI))
      IF((TPIH.LE.200).OR.(JH2.GE.0.5))POSS=2
      IF((TPIH.LE.200).OR.(JH2.GE.0.5))GOTO110
      K=0
C
C  Set up new time temperature arrays to determine FH1 for a
C    broken heating curve
C
      DO 100 I=FINISH,JJ
      K=K+1
      TEMP1(1,K)=TEMP(1,I)
      TIME1(1,K)=TIME(1,I)
      JJ2=K
```

```
100    CONTINUE
C
C  Calculate heat penetration parameters for broken heating
C    curve and calculate GBH
C
       CALL CALC(1,JJ2,DEGDEV(1),RT,CRT,TI,CTI,TIME1,TEMP1,
     C  COMUP,FH1,JH1,FHMIN1,INSUF2,JC,JCMIN,FINISH,B01,B11,FC)
       IF(INSUF2.EQ.1)POSS=3
       IF(INSUF2.EQ.1)GOTO110
       GBH=10**((B01*B12-B02*B11)/(B12-B11))
       POSS=4
110    IF(KM.EQ.1)GOTO120
C
C  Calculate heat penetration parameters for cooling
C
       CALL CALC(2,JK,DEGDEV(2),RT,CRT,TI,CTI,TIME,TEMP,COMUP,
     C  FH,JH,FHMIN,INSUFC,JC,JCMIN,FINISH,B0C,B1C,FC)
       IF(INSUFC.EQ.1)GOTO130
       GOTO140
C
C  Output for table of heat penetration parameters
C
120    IF(POSS.EQ.1)WRITE(2,210)PAGE,KTRIAL
       IF(POSS.EQ.2)WRITE(2,220)PAGE,KTRIAL,JH2,FH2,FHMIN2
       IF(POSS.EQ.3)WRITE(2,230)PAGE,KTRIAL,JH2,FH2,FHMIN2
       IF(POSS.EQ.4)WRITE(2,240)PAGE,KTRIAL,JH1,FH1,FHMIN1,JH2,FH2,
     C  FHMIN2,GBH
       GOTO150
130    IF(POSS.EQ.1)WRITE(2,250)PAGE,KTRIAL
       IF(POSS.EQ.2)WRITE(2,260)PAGE,KTRIAL,JH2,FH2,FHMIN2
       IF(POSS.EQ.3)WRITE(2,270)PAGE,KTRIAL,JH2,FH2,FHMIN2
       IF(POSS.EQ.4)WRITE(2,280)PAGE,KTRIAL,JH1,FH1,FHMIN1,JH2,FH2,
     C  FHMIN2,GBH
       GOTO150
140    IF(POSS.EQ.1)WRITE(2,290)PAGE,KTRIAL,FC,JC,JCMIN
       IF(POSS.EQ.2)WRITE(2,300)PAGE,KTRIAL,JH2,FH2,FHMIN2,FC,JC,JCMIN
       IF(POSS.EQ.3)WRITE(2,310)PAGE,KTRIAL,JH2,FH2,FHMIN2,FC,JC,JCMIN
       IF(POSS.EQ.4)WRITE(2,320)PAGE,KTRIAL,JH1,FH1,FHMIN1,JH2,FH2,
     C  FHMIN2,GBH,FC,JC,JCMIN
C
C  Output for data file of heat penetration results
C
150    IF(KM.EQ.1)GOTO172
       IF(INSUFC.EQ.1)GOTO190
       FCOUT=FC+800.
       GOTO(155,160,165,170),POSS
155    WRITE(1,156)PAGE,KSORT1,KSORT2,KSORT3,FCOUT,JC,KTRIAL,KREP,
     C   KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ,FRATE,AIRPSI
156    FORMAT(I3,3I2,4X,'.',2X,F7.2,2X,'.',2X,F5.2,3I2,2I3,
     C   2F5.1,F5.2,2F5.3,2F5.1)
       WRITE(1,158)KTRIAL
158    FORMAT(3X,' KTRIAL ',I2,' THERE WERE INSUFFICIENT TEMPS FOR '
      C   ,'THE FH CALCULATION')
       GOTO200
160    WRITE(1,163)PAGE,KSORT1,KSORT2,KSORT3,FH2,FCOUT,JH2,JC,KTRIAL,
      C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
      C  ,FRATE,AIRPSI
163    FORMAT(I3,3I2,F7.2,F7.2,2F5.2,3I2,2I3,2F5.1,
      C   F5.2,2F5.3,2F5.1)
       GOTO200
165    WRITE(1,166)PAGE,KSORT1,KSORT2,KSORT3,FH2,JH2,JC,KTRIAL,
      C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
      C  ,FRATE,AIRPSI
166    FORMAT(I3,3I2,4X,'.',2X,F7.2,2F5.2,3I2,2I3,2F5.1,
      C   F5.2,2F5.3,2F5.1)
       WRITE(1,168)KTRIAL
168    FORMAT(3X,' KTRIAL ',I2,' — A BROKEN HEATING CURVE —',
      C   ' INSUFFICIENT TEMPS TO CALCULATE FH1')
       GOTO200
170    WRITE(1,171)PAGE,KSORT1,KSORT2,KSORT3,FH1,FH2,JH2,JC,KTRIAL,
      C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
      C  ,FRATE,AIRPSI
171    FORMAT(I3,3I2,2F7.2,2F5.2,3I2,2I3,2F5.1,F5.2,2F5.3,2F5.1)
       GOTO200
172    CONTINUE
       GOTO(174,178,181,184),POSS
174     WRITE(1,175)PAGE,KSORT1,KSORT2,KSORT3,KTRIAL,KREP,
      C   KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ,FRATE,AIRPSI
175    FORMAT(I3,3I2,4X,'.',6X,'.',4X,'.',4X,'.',2X,3I2,2I3,2F5.1,
      C   F5.2,2F5.3,2F5.1)
       WRITE(1,158)KTRIAL
       GOTO200
178    WRITE(1,179)PAGE,KSORT1,KSORT2,KSORT3,FH2,JH2,KTRIAL,
      C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
      C  ,FRATE,AIRPSI
179    FORMAT(I3,3I2,F7.2,4X,'.',2X,F5.2,2X,'.',2X,3I2,2I3,
      C   2F5.1,F5.2,2F5.3,2F5.1)
       GOTO200
181    WRITE(1,182)PAGE,KSORT1,KSORT2,KSORT3,FH2,JH2,KTRIAL,
      C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
      C  ,FRATE,AIRPSI
182    FORMAT(I3,3I2,4X,'.',2X,F7.2,F5.2,2X,'.',2X,3I2,2I3,2F5.1,
      C   F5.2,2F5.3,2F5.1)
       WRITE(1,168)KTRIAL
       GOTO200
184    WRITE(1,185)PAGE,KSORT1,KSORT2,KSORT3,FH1,FH2,JH2,KTRIAL,
      C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
      C  ,FRATE,AIRPSI
185    FORMAT(I3,3I2,2F7.2,F5.2,2X,'.',2X,3I2,2I3,2F5.1,F5.2,
      C   2F5.3,2F5.1)
       GOTO200
190    CONTINUE
       GOTO(192,194,196,198),POSS
192    WRITE(1,175)PAGE,KSORT1,KSORT2,KSORT3,KTRIAL,KREP,
     C   KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ,FRATE,AIRPSI
      WRITE(1,193)KTRIAL
193   FORMAT(3X,' KTRIAL ',I2,' THERE WERE INSUFFICIENT TEMPS ',
     C   'FOR THE JC CALCULATION')
      WRITE(1,158)KTRIAL
      GOTO200
194   WRITE(1,179)PAGE,KSORT1,KSORT2,KSORT3,FH2,JH2,KTRIAL,
     C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
     C  ,FRATE,AIRPSI
      WRITE(1,193)KTRIAL
      GOTO200
196   WRITE(1,182)PAGE,KSORT1,KSORT2,KSORT3,FH2,JH2,KTRIAL,
     C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
     C  ,FRATE,AIRPSI
      WRITE(1,193)KTRIAL
      WRITE(1,168)KTRIAL
      GOTO200
198   WRITE(1,185)PAGE,KSORT1,KSORT2,KSORT3,FH1,FH2,JH2,KTRIAL,
     C  KREP,KDUM1,KDUM2,KDUM3,RT,TI,COMUP,TCVERT,TCHORZ
     C  ,FRATE,AIRPSI
      WRITE(1,193)KTRIAL
200   CONTINUE
210   FORMAT(//1X,I3,1X,I2,T17,' ',5X,' ',6X,' ',6X,' ',5X,
     C   ' ',6X,' ',5X,' ',7X,'$',7X,'$',4X,'$')
220   FORMAT(//1X,I3,1XI2,T14,F5.2,1X,F6.2,2X,F5.2,3X,
     C   '-----NOT APPLICABLE-----',6X,'$',7X,'$',4X,'$')
230   FORMAT(//1X,I3,1X,I2,T17,' ',5X,' ',6X,' ',3X,F5.2,
     C   1X,F6.2,2X,F5.2,3X,' ',7X,'$',7X,'$',4X,'$')
240   FORMAT(//1X,I3,1X,I2,T14,F5.2,1X,F6.2,2X,F5.2,1X,F5.2,
     C   1X,F6.2,2X,F5.2,1X,F5.1,4X,'$',5X,'$',4X,'$')
250   FORMAT(//1X,I3,1X,I2,T17,' ',5X,' ',6X,' ',6X,' ',5X,
     C   ' ',6X,' ',5X,' ',7X,' ',7X,' ',4X,' ')
260   FORMAT(//1X,I3,1XI2,T14,F5.2,1X,F6.2,2X,F5.2,3X,
     C   '-----NOT APPLICABLE-----',6X,' ',7X,' ',4X,' ')
270   FORMAT(//1X,I3,1X,I2,T17,' ',5X,' ',6X,' ',3X,F5.2,1X,F6.2,
     C   2X,F5.2,3X,' ',7X,' ',7X,' ',4X,' ')
280   FORMAT(//1X,I3,1X,I2,T14,F5.2,1X,F6.2,2X,F5.2,1X,F5.2,
     C   1X,F6.2,2X,F5.2,1X,F5.1,4X,' ',5X,' ',4X,' ')
290   FORMAT(//1X,I3,1X,I2,T17,' ',5X,' ',6X,' ',6X,' ',5X,
     C   ' ',6X,' ',5X,' ',3X,F6.2,1X,F5.2,1X,F5.2)
300   FORMAT(//1X,I3,1XI2,T14,F5.2,1X,F6.2,2X,F5.2,3X,
     C   '-----NOT APPLICABLE-----',2X,F6.2,1X,F5.2,1X,F5.2)
310   FORMAT(//1X,I3,1X,I2,T17,' ',5X,' ',6X,' ',3X,F5.2,1X,F6.2,
     C   2X,F5.2,3X,' ',3X,F6.2,1X,F5.2,1X,F5.2)
320   FORMAT(//1X,I3,1X,I2,T14,F5.2,1X,F6.2,2X,F5.2,1X,F5.2,
     C   1X,F6.2,2X,F5.2,1X,F5.1,1X,F6.2,1X,F5.2,1X,F5.2)
900   WRITE(2,910)
910   FORMAT(///'$ = NO COOLING DATA'/1X,'  = INSUFFICIENT DATA'/1X,
     C   '"NOT APPLICABLE" = NOT A BROKEN HEATING CURVE')
      STOP
      END
C
```

```
C
C
      SUBROUTINE CALC(IND,JJ,DEGDEV,RT,CRT,TI,CTI,TIME,TEMP,
     C   COMUP,FH,JH,FHMIN,INSUF,JC,JCMIN,FINISH,B0,B1,FC)
C
C  This subroutine calculates the heat penetration parameters Fh and
C  Jh or Fc and Jc according to Stumbo (1973).  Times and temperatures
C  must be arranged in the arrays in descending time for both heating
C  and cooling.  The straight line portion of the heating or cooling
C  curve is determined by least squares linear regression of the plot
C  of the log of the temperature differential between the heating or
C  cooling retort temperature and product temperature versus time.
C
C  The subroutine requires 6 time-temperature data pairs before a
C  regression line is calculated.  The regression line, once
C  calculated, is projected to the next time and the projected
C  temperature is compared to the input temperature.  If these two
C  differ by more than DEGDEV, that time-temperature pair is not
C  included in the regression calculation.  The program then checks
C  the next time-temperature pair.  When 5 sequential temperatures
C  are found that do not meet the DEGDEV criteria, the appropriate
C  heat penetration parameters are calculated for those points which
C  met the DEGDEV criteria.
C
C  VARIABLES
C
C    COMUP       Time (min) for retort to reach processing temperature
C    CRT         Cooling retort temperature (F)
C    CTI         Initial product temperature at beginning of
C                  cooling (F)
C    DEGDEV      Maximum difference allowed between input temperature
C                  and projected temperature (F) calculated from
C                  regression line
C    FC          Time for straight line portion of a cooling curve to
C                  transverse one log cycle (min)
C    FH          Time for straight line portion of a heating curve to
C                  transverse one log cycle (min)
C    FHMIN       Number of minutes used to determine regression line
C                  for FH
C    IND         Indicates heating or cooling.  1=heating, 2=cooling
C    INSUF       If insufficient time-temperature pairs are present for
C                  calculation of a regression line, INSUF is assigned
C                  a value of 1
C    J           Counter keeping track of the number of consecutive
C                  time-temperature which do not meet DEGDEV criteria
C    JC          Lag factor for cooling curve
C    JCMIN       Number of minutes used to determine regression line
C                  for FC
C    JH          Lag factor for heating curve
C    JJ          Number of time-temperature pairs
C    TEMP(X, )   Array containing input times (min)
C                  X=1 heating
```

```
C                 X=2 cooling
C    TI          Initial product temperature before heating
C    TIME(X, )   Array containing input times (min)
C                 X=1 heating
C                 X=2 cooling
C    RT          Heating retort temperature (F)
C
C
      DIMENSION TEMP(2,50),TIME(2,50)
      INTEGER DEGDEV,FINISH
      REAL JH,JC,JCMIN
      SX=0.
      SX2=0.
      SY=0.
      SXY=0.
      FH=0.
      JH=0.
      FHMIN=0.
      FC=0.
      JC=0.
      JCMIN=0.
      INSUF=0
      N=0
      J=0
      III=5
C
C  Determine if enough time-temperatures are present to calculate
C    regression line
C
      IF(JJ.GT.5)GOTO10
      INSUF=1
      GOTO60
C
C  The following DO-loop forms the appropriate sums and calculates a
C    regression line
C
10    DO 30 I=1,JJ
      IF(I.LT.6)GOTO20
C
C  Calculate regression coefficients
C
      B1=(SXY-SX*SY/N)/(SX2-(SX**2)/N)
      BO=(SY/N)-B1*SX/N
      T=10**(BO+TIME(IND,I)*B1)
C
C  Determine if temperature projected by regression line matches
C    measured temperature within DEGDEV
C
      IF(IND.EQ.1)TDIF=ABS((RT-TEMP(1,I))-T)
      IF(IND.EQ.2)TDIF=ABS((TEMP(2,I)-CRT)-T)
      IF(TDIF.LT.DEGDEV)GOTO17
      J=J+1
```

```
C
C  If 5 temperatures in a row did not match the temperatures predicted
C    by the regression line. Calculate heat penetration parameters
C
      IF(J.EQ.5)GOTO13
      GOTO30
13    FINISH=I
      GOTO40
17    J=0
      III=I
20    IF(IND.EQ.1)Y=ALOG10(RT-TEMP(1,I))
      IF(IND.EQ.2)Y=ALOG10(TEMP(2,I)-CRT)
C
C  Form appropriate sums for regression calculation
C
      SX=SX+TIME(IND,I)
      SX2=SX2+TIME(IND,I)**2
      SY=SY+Y
      SY2=SY2+Y**2
      SXY=SXY+TIME(IND,I)*Y
      N=N+1
30    CONTINUE
40    IF(IND.EQ.2)GOTO50
C
C  Calculate FH, JH, and FHMIN
C
      FH=-1/B1
      JH=(10**(B0+B1*COMUP*0.6))/(RT-TI)
      FHMIN=TIME(1,1)-TIME(1,III)
      GOTO60
C
C  Calculate FC, JC, and JCMIN
C
50    JC=(10**B0)/(CTI-CRT)
      JCMIN=TIME(2,1)-TIME(2,III)
      FC=-1.0/B1
60    RETURN
      END
```

APPENDIX D
PROGRAM TO SIMULATE HEAT PENETRATION INTO A RETORT POUCH WITH ENTRAPPED AIR PRESENT

```
C  This program calculates heat penetration for both heating and
C  cooling of a retort pouch containing entrapped air.  The
C  program used the fowrard direction finite difference method
C  for an infinite slab geometry.  An infinite Biot number is
C  assumed.
C
C  The height of air above the infinite slab was determined by
C  the top surface area of the slab being modeled, the amount
C  of air present, and the contribution of water vapor of the
C  food to the volume of air present at the different
C  temperatures and pressures.  The activity of the water was
C  assumed to be 1.0 at the slab's top surface temperature.
C  The height of the air at the center of the pouch was used
C  as the height of entrapped air above the infinite slab and
C  was calculated assuming a parabolic decrease in height from
C  the center to the edges of the slab.  The entrapped air
C  above the infinite slab was assumed to be equilibrated
C  with the retort pressure.  A provision for maximum expansion
C  allowed by a confining rack system was included.  Expansion
C  was assumed to be unrestricted by the presence of pouch
C  material.  The air layer was assumed to heat by conduction,
C  and was calculated using the Fourier equation alone and not
C  by finite difference techniques.  Come up and cool down
C  behavior of temperature was patterned after the institutional
C  size pouch retort at FSHN, Univ. of Florida.
C
C  The program also contains provisions for the calculation of
C  retention of a quality factor.
C
C  The program will iterate with different decreasing heating
C  times until the Fo value of the process is less than the
C  terminal Fo value (FOT).  Calculation of a specific process
C  run terminates when the center temperature during cooling is
C  less than 120 F or the termination iteration counter is
C  exceeded.
C
C  VARIABLES
C
C     AK=Thermal conductivity of air-water vapor mixture
C          (BTU/hr ft F)
C     AL=Height of entrapped air above center of pouch
C     ALMAX=Maximum height of air expansion allowed by rack system
```

```
C     ALPHA=Thermal diffusivity of pouch contents (in**2/min)
C     APP=Air partial pressure in headspace
C     AREA=Surface area of pouch covered by gas (in**2)
C     AX=Total heat penetration distance (in)
C     COMDN=Time for retort to reach constant cooling temp (min)
C     COMUP=Time for retort to reach constant heating temp (min)
C     CONC=Accumulator for CQ within iteration
C     CONS1,CONS2,CONS3,CONS4=Dimensionless constants for heat pen.
C     CP=Heat capacity of headspace mixture (BTU/lb F)
C     CQAVE=Average conc. of qual. fact. in that iteration (?/g)
C     CQ( )=Qual. fact. conc. array (?/g)
C     CUT=Come up time iteration number
C     DEC1, DEC2=Fract. temperatures of 200 and 250 F
C     DELX=Incremental distance across AX (in)
C     EA=Energy of activation (Kcal/mole)
C     FK=Thermal conductivity of food (BTU/hr ft F)
C     FO( )=Fo value within iteration across AX (min @ 250 F)
C     FOC=Incremental Fo at center (min @ 250 F)
C     FOCENT=Accumulated Fo at center (min @ 250 F)
C     FOI=Incremental integrated Fo (min @ 250 F)
C     FOINT=Accumulated integrated Fo (min @ 250 F)
C     FOSE=Accumulator for Simpson's rule (FOINT @ J=even)
C     FOSEC=Accumulator for Simpson's rule (FOCENT @ J=even)
C     FOSO=Accumulator for Simpson's rule (FOINT @ J=odd)
C     FOSOC=Accumulator for Simpson's rule (FOCENT @ J=odd)
C     FOT=Terminal Fo value (min)
C     ICEN=# of center temperature node
C     IHEAT=# of iterations for heating cycle (includes CUT)
C     ITERM=Maximum # of iterations for heating and cooling
C     L=Array # distance increment (1=surface, LC=center)
C     LC=Array # for distance increment at center
C     LX=# of distance increments--must be odd integer
C     MIN=# iterations per minute
C     PT=Current process time (min)
C     RHO=Density of headspace mixture (lb/ft**3)
C     RK=Incremental reaction rate constant at L (min**-1)
C     RKO=Freq. factor for Arrhenius eqn. (min**-1)
C     RTI=Initial retort temp
C     RTH=Heating retort temp
C     RTC=Cooling retort temp
C     RK1=Constant for Arrhenius eqn ( F)
C     RT=Iteration retort temperature ( F)
C     RT1=Retort temp. for heating or cooling of previous
C           increment ( F)
C     RTC1=Retort temp. constants for cooling
C     RTPSI=Retort operating presure (PSIG)
C     RTS=Fract. temp. of 230 F
C     RTSS=Fract. temp. constant for linear heating
C     SIMP=Simpson's rule constant
C     SPAN=Difference between retort temperature and lowest exp.
C            temp. (F)
C     SPANX,SPANY=Constants for conv. between fract. and real temp.
```

```
C     T( )=Temperature array --fractional basis
C     TG=Temperature of included gas when measured (F)
C     TIMC=Time to cooling (min)
C     TIME=Time increment--must be integer divisor of 1 min (min)
C     TP( )=Temperature array--real basis (F)
C            TP(LC)=Surface temp
C     TPI=Intial temp. of pouch contents ( F)
C     TT( )=Temperature array--fract basis for previous increment
C     VG=Volume of included gas at TG (in**3)
C     WPP=Water partial pressure in headspace
C     WV=Water vapor pressure in headspace, determined by regression
C          equation of steam table (PSIA)
C     Z=Z value for Fo calculations ( F)
C     ZZ=Lethality conv. factor
C
C
      DIMENSION T(35),TP(35),TT(35),CQ(35),FO(35)
       OPEN(UNIT=5,FILE='SLABGA.DAT',STATUS='OLD',
     C   RECORDTYPE='VARIABLE')
       OPEN(UNIT=6,FILE='SLABGA.RES',STATUS='NEW')
      DO 610 JJ=1,25
      READ(5,*,END=900)LX,AX,TIME,ITERM,IHEAT,ALMAX
      IF(LX.EQ.0)GO TO 620
      READ(5,*)RTI,RTH,RTC,TPI,COMUP,ALPHA
      READ(5,*)Z,RKO,EA,FOT
      READ(5,*)VG,TG,AREA,RTPSI,FK
121   FORMAT(6F5.1)
      TIMC=TIME*IHEAT
      LS=LX-1
C
C  Initial output
C
      WRITE(6,130)AX,LS,TIME,TIMC
130   FORMAT(5X,'SLAB  THICKNESS = ',F5.3,' IN. DIVIDED INTO ',
     CI2,' INCREMENTS',/,5X,'TIME INTERVAL = ',F5.3,' MIN.',
     C'     HEATING TIME = ',F5.2,' MIN.')
      WRITE(6,131)RTI,RTH,RTC,TPI,COMUP,ALPHA,VG
131   FORMAT(5X,'TEMPERATURES--RETORT(INITIAL)=',F5.1,
     C'F    RETORT(HEATING)= ',F5.1,'F',/,5X,'RETORT(COOLING)=',F5.1,
     C'F    POUCH(INITIAL)=',F5.1,'F',/,5X,'COMEUP TIME = ',F5.2,
     C' MIN',/,5X,'THERMAL DIFUSIVITY = ',
     CE10.4,' IN2/MIN'//
     C5X,'GAS VOLUME = ',F7.3,' IN3')
      DELX=AX/(LX-1)
      CONS1=2*ALPHA*TIME/DELX**2
      CONS3=CONS1/2
      WRITE(6,132)Z,EA,RKO,CONS3
132   FORMAT(5X,'Z VALUE = ',F5.1,4X,'ACT. ENERGY = ',
     CF5.2,' KCAL/MOLE    FREQ. FACT. = ',E10.4,' MIN-1',/,5X,
     C'STABILITY CRITERIA = ',F7.5,//,5X,
     C'TEMPERATURES FROM SURFACE TO SURFACE',//)
C
```

```
C  Check stability
C
      IF(CONS3.LT.0.5)GO TO 134
      WRITE(6,133)
133   FORMAT(//,5X,'STABILITY CRITERIA NOT MET',//)
      GO TO 610
134   MIN=1/TIME
      LC=LX+1
      SIMP=1/(LS*3.0)
      RTPSI=RTPSI+14.69
      XVOL=.1469E2*VG/(RTPSI*(TG+460))
      ICEN=1+LS/2
      CUT=COMUP/TIME
      IF(TPI.LT.RTC)SPANX=TPI
      IF(RTC.LE.TPI)SPANX=RTC
      SPAN=RTH-SPANX
      TPI=(TPI-SPANX)/SPAN
      DEC1=(.2E3-SPANX)/SPAN
      DEC2=(.25E3-SPANX)/SPAN
      DEC3=(.12E3-SPANX)/SPAN
      RTC=(RTC-SPANX)/SPAN
      RTCC=1.0-RTC
      ZZ=Z/SPAN
      SPANY=SPANX+.45969E3
      RTS=(.23E3-SPANX)/SPAN
      RTSS=(1.0-RTS)/(CUT-MIN)
      RK1=EA*.9066E3
135   IC=IHEAT+1/TIME+1
      FOINT=0.0
      FOCENT=0.0
      RT1=RTS
      FOSE=0.0
      FOSO=0.0
      FOSEC=0.0
      FOSOC=0.0
C
C  Initalize TEMP and CONC arrays
C
      DO 140 L=1,LC
      TT(L)=TPI
      FO(L)=0.0
140   CQ(L)=1.0
      T(LX)=TPI
C
C  Iterate for temperature versus time
C
      DO 600 J=1,ITERM
C
C  Correct RT for comup or cooling temp. changes
C
      IF(J.LT.MIN)GO TO 600
      IF(J.GE.IC)GO TO 201
      IF(J.GT.CUT)GO TO 200
      RT=RTS+RTSS*(J-MIN)
      GO TO 205
200   RT=1.0
      GO TO 205
C
C  Cooling power function represents response for FSHN retort only
C
201   RT=RTC+RTCC/((J-IHEAT)*TIME)**1.65
C
C  Calculate temperature profile
C
205   T(1)=RT
      DO 210 I=2,LS
210   T(I)=TT(I)+CONS3*(TT(I-1)-2*TT(I)+TT(I+1))
      TGA=((TT(LC)+TT(LX))/2)*SPAN+SPANX
      TSA=T(LX)*SPAN+SPANX
      VOL=XVOL*(TGA+460)
      WV=-.96798E1+.25934*TSA-.22434E-2*TSA**2+.73691E-5*TSA**3
      WPP=WV/RTPSI
      APP=1.-WPP
      AL=2.25*VOL/(APP*AREA)
       IF(AL.GT.ALMAX)AL=ALMAX
      AK=WPP*(.82953E-2+.26807E-4*TGA)+APP*(.1255E-1+.1951E-4*TGA)
      T(LC)=RT
      CONS4=CONS1*DELX*AK/(FK*AL)
      T(LX)=TT(LX)*(1-CONS1-CONS4)+TT(LS)*CONS1+TT(LC)*CONS4
      IF(J.GT.IC)GO TO 215
      IF(T(1).GT.RT)T(1)=RT
      IF(T(LX).GT.T(LC))T(LX)=T(LC)
215   FOI=0.0
C
C  Calculate average interval temperature
C  Calculate Fo and qual. fact. conc.
C
      DO 216 I=1,LC
216   TT(I)=T(I)
      DO 230 I=1,LX
      RK=RK0/EXP(RK1/(T(I)*SPAN+SPANY))
      IF(RK.LT.0.1E-4)GO TO 225
      CQ(I)=CQ(I)-CQ(I)*TIME*RK
225   IF(T(I).LT.DEC1)GO TO 227
      IF(T(I).LT.DEC2)GO TO 226
      FO(I)=TIME*10**((T(I)-DEC2)/ZZ)
      GO TO 230
226   FO(I)=TIME/10**((DEC2-T(I))/ZZ)
      GO TO 230
227   FO(I)=0.0
230   CONTINUE
      DO 235 I=2,LS,2
235   FOI=FOI+4*FO(I)+2*FO(I+1)
      FOI=SIMP*(FOI+FO(1)-FO(LC))
      RT1=RT
      IF(T(1).LT.DEC2)GO TO 240
      FOC=TIME*10**((T(ICEN)-DEC2)/ZZ)
      GO TO 250
240   FOC=TIME/10**((DEC2-T(ICEN))/ZZ)
250   IF(J/2*2.EQ.J)GO TO 251
      FOCENT=(FOSOC+FOC)/3
      GO TO 252
251   FOCENT=(FOSEC+FOC)/3
C
C  If center Fo value is greater than specified terminal Fo,
C    process is repeated with shorter heating time
C
252   IF(FOT.LT.0.1)GO TO 253
      IF(FOCENT.LT.FOT)GO TO 253
      IHEAT=IHEAT-MIN
      TIMC=IHEAT*TIME
      WRITE(6,254)TIMC
254   FORMAT(//,5X,'REITERATE WITH A HEATING TIME OF ',F5.2,' MIN',/)
      GO TO 135
253   IF(J/MIN*MIN.NE.J)GO TO 330
      CONC=0.0
      DO 256 I=1,LC
256   TP(I)=T(I)*SPAN+SPANX
      DO 255 I=2,LS,2
255   CONC=CONC+4*CQ(I)+2*CQ(I+1)
      CQAVE=SIMP*(CONC+CQ(1)-CQ(LC))
      IF(J/2*2.NE.J)GO TO 260
      FOINT=(FOSE+FOI)/3
      FOCENT=(FOSEC+FOC)/3
      GO TO 270
260   FOINT=(FOSO+FOI)/3
      FOCENT=(FOSOC+FOC)/3
270   PT=J*TIME
      RTR=RT*SPAN+SPANX
C
C  Output
C
      WRITE(6,300)PT,RTR
300   FORMAT(5X,'PROCESS TIME = ',F5.1,' MINUTES',5X,
     C'RETORT TEMPERATURE = ',F5.1,' F',/)
      WRITE(6,310)(TP(L),L=1,LC)
310   FORMAT(1X,20(1X,F5.1))
      WRITE(6,320)CQAVE,FOINT,FOCENT,AL
320   FORMAT(/,5X,'AVERAGE QUAL. FACT. CONC. = ',F8.6,/,5X,
     C'INTEGRATED FO = ',F5.2,' MINUTES',/,5X,
     C'CENTER POINT FO = ',F5.2,' MINUTES',/,
     C5X,'THICKNESS OF AIR SPACE (IN) = ',F8.6,//)
330   IF(J/2*2.NE.J)GO TO 340
      FOSE=FOSE+2*FOI
      FOSEC=FOSEC+2*FOC
      FOSO=FOSO+4*FOI
      FOSOC=FOSOC+4*FOC
      GO TO 350
340   FOSO=FOSO+2*FOI
      FOSOC=FOSOC+2*FOC
      FOSE=FOSE+4*FOI
      FOSEC=FOSEC+4*FOC
350   IF(J.LE.IC)GO TO 600
      IF(T(ICEN).LT.DEC3)GO TO 610
600   CONTINUE
610   CONTINUE
620   CONTINUE
900   STOP
      END
```

APPENDIX E
PROGRAM TO FIT TEMPERATURE DISTRIBUTION DATA TO CUBIC FUNCTION

```
C   Program to fit temperature data from slab 4 to a cubic
C     polynomial by least squares (Draper and Smith,1966).
C   The temperature of the bottom of the slab was assumed to
C     be 250 F, this gave the fifth set of data points necessary
C     for an effective least squares analysis.
C   Variable names follow conventions in Draper and Smith (1966)
C     (Chapter 2)
C   This program will also calculate a polynomial for the other
C     polycarbonate slabs.  The only adjustment needed is to
C     input values for thermocouple position (inches from top)
C     of the appropriate slab in the X array.
C   Adjusted to assign 250F to top of slab if original
C     regression equation estimates a top temp exceeding
C     250F.
C
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 ICALC(8,4),INVXPX(4,4),NYSQ
      DIMENSION X(4,6),XPX(4,4),XPY(4),Y(6),B(4),BDERIV(3)
C
C   The following OPEN statements allow data to be read from the
C     file POLYNO.DAT and cause the program output to be placed
C     in the file POLYNO.RES. The file POLYNO.DAT must be
C     present for the program to run.
C
      OPEN(UNIT=5,FILE='POLYNO.DAT',STATUS='OLD',
     C   RECORDTYPE='VARIABLE')
      OPEN(UNIT=6,FILE='POLYNO.RES',STATUS='NEW')
15    READ(5,*,END=900)TIME,Y(1),Y(2),Y(3),Y(4)
      IND=0
      Y(5)=250.
      DO 2 I=1,4
       XPY(I)=0.
       B(I)=0.
2     CONTINUE
      DO 4 I=1,4
      DO 4 J=1,4
       XPX(I,J)=0.
4     CONTINUE
      DO 6 I=1,8
      DO 6 J=1,4
       ICALC(I,J)=0.
6     CONTINUE
```

```
C
C   Initialize X Array
C
      X(2,1)=.469
      X(2,2)=.625
      X(2,3)=.781
      X(2,4)=1.156
      X(2,5)=1.5
      DO 10 I=1,5
       X(1,I)=1.0
10    CONTINUE
      DO 20 I=3,4
      DO 20 J=1,5
       X(I,J)=X(2,J)**(I-1)
20    CONTINUE
C
C   Calculate X'X (XPX)
C
      DO 100 K=1,4
      DO 100 J=1,4
      DO 100 I=1,5
       XPX(J,K)=XPX(J,K)+X(K,I)*X(J,I)
100   CONTINUE
C
C   Calculate inverse of X'X (XPX)
C
C    Load ICALC array
C
      DO 200 I=1,4
      DO 200 J=1,4
       ICALC(I,J)=XPX(I,J)
200   CONTINUE
      DO 210 I=1,4
       J=I+4
       ICALC(J,I)=1.0
210   CONTINUE
C
C    Calculate inverse of XPX (INVXPX) by performing elementary
C      row operations on ICALC array
C
      DO 250 J=1,4
       DIV=ICALC(J,J)
       DO 220 I=1,8
        ICALC(I,J)=ICALC(I,J)/DIV
220    CONTINUE
       DO 240 K=1,4
        IF(K.EQ.J)GOTO240
        C=ICALC(J,K)
        DO 230 L=1,8
         ICALC(L,K)=ICALC(L,K)-(C*ICALC(L,J))
230     CONTINUE
240    CONTINUE
```

```
250     CONTINUE
        DO 260 I=1,4
        DO 260 J=1,4
         K=I+4
         INVXPX(I,J)=ICALC(K,J)
260     CONTINUE
C
C   Calculate X'Y (XPY)
C
        DO 300 J=1,4
        DO 300 I=1,5
         XPY(J)=XPY(J)+(X(J,I)*Y(I))
300     CONTINUE
C
C   Calculate B by multiplying INVXPXBY by XPY
C
        DO 400 J=1,4
        DO 400 I=1,4
         B(J)=B(J)+INVXPX(I,J)*XPY(I)
400     CONTINUE
C
C   The following regression is preformed if the predicted
C       temp of the top of the slab exceeds 250F.
C
        IF(B(1).GT.250.)THEN
        IND=1
        Y(6)=250.
        X(1,6)=1.0
        DO 700 I=2,4
         X(I,6)=0.0
700     CONTINUE
        DO 710 I=1,4
         XPY(I)=0.
         B(I)=0.
710     CONTINUE
        DO 720 I=1,4
        DO 720 J=1,4
         XPX(I,J)=0.
720     CONTINUE
        DO 730 I=1,8
        DO 730 J=1,4
         ICALC(I,J)=0.
730     CONTINUE
C
C   Calculate X'X (XPX)
C
        DO 740 K=1,4
        DO 740 J=1,4
        DO 740 I=1,6
         XPX(J,K)=XPX(J,K)+X(K,I)*X(J,I)
740     CONTINUE
C
```

```
C   Calculate inverse of X'X (XPX)
C
C    Load ICALC array
C
       DO 750 I=1,4
       DO 750 J=1,4
        ICALC(I,J)=XPX(I,J)
750    CONTINUE
       DO 760 I=1,4
        J=I+4
        ICALC(J,I)=1.0
760    CONTINUE
C
C    Calculate inverse of XPX (INVXPX) by performing elementary
C      row operations on ICALC array
C
       DO 800 J=1,4
        DIV=ICALC(J,J)
        DO 770 I=1,8
         ICALC(I,J)=ICALC(I,J)/DIV
770     CONTINUE
        DO 790 K=1,4
         IF(K.EQ.J)GOTO790
         C=ICALC(J,K)
         DO 780 L=1,8
          ICALC(L,K)=ICALC(L,K)-(C*ICALC(L,J))
780      CONTINUE
790     CONTINUE
800    CONTINUE
       DO 810 I=1,4
       DO 810 J=1,4
        K=I+4
        INVXPX(I,J)=ICALC(K,J)
810    CONTINUE
C
C   Calculate X'Y (XPY)
C
       DO 820 J=1,4
       DO 820 I=1,6
        XPY(J)=XPY(J)+(X(J,I)*Y(I))
820    CONTINUE
C
C   Calculate B by multiplying INVXPXBY by XPY
C
       DO 830 J=1,4
       DO 830 I=1,4
        B(J)=B(J)+INVXPX(I,J)*XPY(I)
830    CONTINUE
       ENDIF
C
C   Calculate R-squared (RSQ)
C
```

```
      IF(IND.EQ.0.)THEN
      YSUM=0.0
      DO 500 I=1,5
       YSUM=YSUM+Y(I)
500   CONTINUE
      NYSQ=YSUM**2/5.
C
C     Calculate B'X'Y (BPXPY) and Y'Y (YPY)
C
      BPXPY=0.0
      YPY=0.0
      DO 510 I=1,4
       BPXPY=BPXPY+B(I)*XPY(I)
       YPY=YPY+Y(I)**2
510   CONTINUE
      YPY=YPY+Y(5)**2
      RSQ=(BPXPY-NYSQ)/(YPY-NYSQ)
      ELSE
      YSUM=0.0
      DO 520 I=1,6
       YSUM=YSUM+Y(I)
520   CONTINUE
      NYSQ=YSUM**2/6.
C
C     Calculate B'X'Y (BPXPY) and Y'Y (YPY)
C
      BPXPY=0.0
      YPY=0.0
      DO 530 I=1,4
       BPXPY=BPXPY+B(I)*XPY(I)
       YPY=YPY+Y(I)**2
530   CONTINUE
      YPY=YPY+Y(5)**2+Y(6)**2
      RSQ=(BPXPY-NYSQ)/(YPY-NYSQ)
      ENDIF
C
C   Calculate derivative of prediction equation and roots of
C     derivative using quadratic formula.  BDERIV is array where
C     coefficients of derivative are stored.
C
      BDERIV(3)=3.*B(4)
      BDERIV(2)=2.*B(3)
      BDERIV(1)=B(2)
      S=BDERIV(2)**2-4.*BDERIV(3)*BDERIV(1)
      IF(S.GT.0.0)THEN
       ROOT1=(-BDERIV(2)+SQRT(S))/(2.*BDERIV(3))
       ROOT2=(-BDERIV(2)-SQRT(S))/(2.*BDERIV(3))
       WRITE(6,600)
600    FORMAT(//5X,'------------------------------',
     C     '--------------------------------------------')
       WRITE(6,610)TIME,Y(1),Y(2),Y(3),Y(4),B(4),
     C   BDERIV(3),B(3),BDERIV(2),B(2),BDERIV(1),B(1)
```

```
610      FORMAT(//11X,'TIME =',F5.1,' MIN',9X,'TEMPS -',
     C     4(1X,F5.1)//22X,'POLYMONIAL',T57,
     C     'DERIVATIVE'/22X,'----------',T57,'----------'/
     C     18X,'X**3 * ',E14.6,T53,'X**2 * ',E14.6/
     C     18X,'X**2 * ',E14.6,T53,'X**1 * ',E14.6/
     C     18X,'X**1 * ',E14.6,T53,'X**0 * ',E14.6/
     C     18X,'X**0 * ',E14.6)
         WRITE(6,620)ROOT1,ROOT2
620      FORMAT('0',T15,'ROOTS OF DERIVATIVE - ',E14.6/T37,E14.6)
        IF((ROOT1.LT.1.5).AND.(ROOT1.GT.0.))
     C    TMIN=B(1)+ROOT1*(B(2)+ROOT1*(B(3)+ROOT1*B(4)))
        IF((ROOT2.LT.1.5).AND.(ROOT2.GT.0.))
     C    TMIN=B(1)+ROOT2*(B(2)+ROOT2*(B(3)+ROOT2*B(4)))
        WRITE(6,625)TMIN
625     FORMAT('0',T15,'MINIMUM TEMPERATURE = ',F5.1)
        ELSE
         WRITE(6,600)
         WRITE(6,610)TIME,Y(1),Y(2),Y(3),Y(4),B(4),
     C     BDERIV(3),B(3),BDERIV(2),B(2),BDERIV(1),B(1)
         WRITE(6,630)
630      FORMAT('0',T15,'ROOTS OF DERIVATIVE ARE IMAGINARY')
        ENDIF
        WRITE(6,640)RSQ
640     FORMAT('0',T15,'R-SQUARED = ',F6.4)
C
C  The variable POINT is the calculated temp at the input
C    positions of slab 4 (these should match the input temps)
C
        WRITE(6,650)
650     FORMAT(//23X,'X',4X,'TEMP',T45,'X',5X,'TEMP'/22X,
     C  '---  ------',T43,'-----  -----')
        XX=0.1
        DO 670 I=1,4
         XX=0.1+XX
         TEMP=B(1)+XX*(B(2)+XX*(B(3)+XX*B(4)))
         POINT=B(1)+X(2,I)*(B(2)+X(2,I)*(B(3)+X(2,I)*B(4)))
         WRITE(6,660)XX,TEMP,X(2,I),POINT
660      FORMAT(T22,F3.1,T27,F6.1,T43,F5.3,2X,F5.1)
670     CONTINUE
        DO 680 I=1,9
         XX=0.1+XX
         TEMP=B(1)+XX*(B(2)+XX*(B(3)+XX*B(4)))
         WRITE(6,660)XX,TEMP
680     CONTINUE
        IF(IND.EQ.1)WRITE(6,690)
690     FORMAT('0',T15,'NOTE:  Regression was done twice, ',
     C    'the top of the slab was set to 250F for these results.')
        GOTO15
900     STOP
        END
```

APPENDIX F

FINITE DIFFERENCE PROGRAM TO SIMULATE A THERMAL PROCESS DETERMINATION; FINITE BIOT NUMBER

```
C  This program simulates heat penetration into an infinite slab
C  for both heating and cooling processes with a finite Biot
C  number.  The program uses the forward direction finite difference
C  method for an infinite slab geometry.  It will determine a
C  process time by iteration for a given F-value at any given node
C  in the infinite slab.  The process time predicted is accurate
C  to within 0.005 min. or to within half the time increment,
C  whichever is larger.  The F-value is determined in two ways:
C  at each time increment the F-value is integrated using the
C  Trapezoid rule, and the F-value is also determined by
C  integrating the data obtained every full minute by Simpson's
C  rule.  The F-value determined at every iteration is used for
C  process determination.
C
C  The program assumes a linear come up time from an initial retort
C  temperature after a specified delay to the processing temperature.
C  An exponential cool down profile is used.
C
C  The program terminates for a given set of input after the desired
C  process time has been found and either the center slab temperature
C  is within 5 F of the cooling retort temperature or the maximum
C  process time has been exceeded.
C
C  Heat penetration parameters, Fh, Jh, Fc, and Jc are calculated
C  for the heating and cooling curves found for each set of input
C  data.
C
C  VARIABLES
C
C     ALPHA=Thermal diffusivity of pouch contents (in**2/min)
C     AX=Total heat penetration distance (in)
C     BIOTC=Cooling water Biot number (BIOTC=(H-VALUE*DELX)/K-VALUE)
C     BIOTH=Heating Biot number
C     CDT=Come down time (min)
C     CIND=Indicates zero cooling time and end of heating
C     COMDN=Time for retort to reach constant cooling temp. (min)
C     COMUP=Time for retort to reach constant heating temp. (min)
C     CONS1,CONS2,CONS3=Dimensionless constants for heat pen.
C     COOLEX=Exponent used to describe comedown temp. profile
C     CUT=Come up time iteration number
C     DE=# of time increments before retort sees increase in
C            temperature at beginning of process
```

```
C     DEC1=Fract. temperature 4 Z-values from retort temperature
C     DEC2=Fract. temperature of 250 F
C     DEC3=Fract. temperature 5 F above cooling retort temperature
C     DELAY=Time (min) before retort sees increase in temperature at
C            beginning of process
C     DELX=Incremental distance across AX (in)
C     FHFC( , )=Array containing FH, JH, FC, and JC values
C     FOC( )=Array containing incremental Fo at all positions
C              (min @ 250 F)
C     FOT=Fo desired for position NN; if FOT=0, program calculates
C               temps for the input heating time only
C     FOTEST( )=Array containing accumulated Fo at all positions
C               (min @ 250 F,integrated by trapezoid rule)
C     H=Surface heat transfer coefficient (BTU/hr ft**2 F)
C     IC=# of iterations until cooling starts
C     IHEAT=# of iterations for heating cycle (includes CUT)
C     IND=Counter, number of minutes into the process
C     ITERM=Maximum # of iterations for heating and cooling
C     K=Thermal conductivity (BTU/hr ft F)
C     L=Array # distance increment (1=surface, LC=center)
C     LC=Array # for distance increment at center
C     LX=# of distance increments--must be even integer
C     MIN=# iterations per minute
C     NN=Position number (node) that process is designed for
C          (center=1)
C     PT=Current process time (min)
C     RESULT( , )=Array containing output
C     RT=Iteration retort temperature ( F)
C     RT1=Retort temp. for heating or cooling of previous
C           increment ( F)
C     RTC1=Retort temp. constants for cooling
C     RTS=Fract. temperature of initial retort temperature
C     RTSS=Fract. temp. constant for linear heating
C     SPAN=Difference between retort temperature and lowest exp.
C            temp. (F)
C     SPANX,SPANY=Constants for conv. between fract. and real temp.
C     T( )=Temperature array --fractional basis
C     TBEGIN=Retort temperature at zero time
C     TEMPFC( )=Temperature array for FC calculation
C     TEMPFH( )=Temperature array for FH calculation
C     TIMC=Time to cooling (min)
C     TIMEFC( )=Time array for FC calculation
C     TIMEFH( )=Time array for FH calculation
C     TIMTOT=Maximum process time (min)
C     TIME=Time increment--must be integer divisor of 1 min (min)
C     TP( )=Temperature array--real basis (F)
C     TPI=Intial temp. of pouch contents ( F)
C     TT( )=Previous temperature array--fractional basis
C     Z=Z value for Fo calculations ( F)
C     ZZ=Lethality conv. factor
C
C
```

```
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION T(25),TP(25),TT(25),RESULT(25,300),FO(25),
     C  TIMEFH(10),TIMEFC(10),TEMPFH(10),TEMPFC(10),FHFC(25,4),
     C  FOC(25),FOTEST(25)
      INTEGER CIND,RUNNUM
      REAL*8 JH,JC,K
      OPEN(UNIT=5,FILE='SLABFDWP.DAT',STATUS='OLD',
     C  RECORDTYPE='VARIABLE')
      OPEN(UNIT=6,FILE='SLABFDWP.RES',STATUS='NEW')
      OPEN(UNIT=1,FILE='SLB.SAS',STATUS='NEW')
      DO 610 JJ=1,150
      READ(5,*,END=620)RUNNUM,LX,AX,TIME,TIMC,TIMTOT
      READ(5,*)RTH,RTC,TPI,COMUP,ALPHA
      READ(5,*)DELAY,TBEGIN,COMDN,COOLEX
      READ(5,*)Z,FOT,NN,H,K
      BIOTH=(H*(AX/LX)/12.)/K
      BIOTC=BIOTH
      IHEAT=TIMC/TIME
      ITERM=TIMTOT/TIME
      WRITE(6,130)RUNNUM,AX,LX,TIME,TIMC
130   FORMAT('1',4X,'RUN NUMBER',I4/5X,'--------------'///5X,
     C'SLAB HALF THICKNESS = ',F5.3,' IN. DIVIDED INTO ',
     CI2,' INCREMENTS',/,5X,'TIME INTERVAL = ',F5.3,' MIN.',
     C'     HEATING TIME = ',F6.2,' MIN.')
      WRITE(6,131)RTH,RTC,TPI,COMUP,ALPHA,BIOTH,BIOTC
131   FORMAT(5X,
     C'RETORT(HEATING)= ',F5.1,'F',/,5X,'RETORT(COOLING)=',F5.1,
     C'F    POUCH(INITIAL)=',F5.1,'F',/,5X,'COMEUP TIME = ',F5.2,
     C' MIN',/,5X,'THERMAL DIFUSIVITY = ',
     CE10.4,' IN2/MIN',/,5X,'BIOT NUMBERS--HEATING = ',F7.3,
     C'    COOLING = ',F7.3)
      WRITE(6,129)K,H,DELAY,TBEGIN,COMDN,COOLEX
129   FORMAT(5X,'K = ',F6.4,' BTU/HR FT F'/5X,'H = ',
     C  F5.1,' BTU/HR FT**2 F'/5X,'DELAY BEFORE POUCHES SEE RETORT ',
     C  'TEMPERATURE INCREASE = ',F5.2,' MIN'/5X,
     C  'RETORT TEMP POUCHES EXPOSED TO IMMEDIATELY AFTER DELAY'
     C  ' = ',F5.1,'F'/5X,'COOL DOWN TIME = ',F4.1,' MIN'/5X,
     C  'EXPONENT USED IN CALCULATING COOL DOWN PROFILE = ',
     C  F5.3)
      DELX=AX/LX
      CONS1=2*ALPHA*TIME/DELX**2
      CONS3=CONS1/2
      WRITE(6,132)Z,NN
132   FORMAT(5X,'Z VALUE = ',F5.1,5X,'TEST Fo NODE = ',
     C  I2,'  (CENTER=1)'//5X)
      IF((DELX**2/(ALPHA*TIME)).GE.(2.*BIOTH+2.))GO TO 134
      WRITE(6,133)
133   FORMAT(//5X,'STABILITY CRITERIA NOT MET'//)
      GO TO 610
134   MIN=1/TIME
      LC=LX+1
      CUT=COMUP/TIME
      IF(TPI.LT.RTC)SPANX=TPI
      IF(RTC.LE.TPI)SPANX=RTC
      SPAN=RTH-SPANX
      TI=TPI
      TPI=(TPI-SPANX)/SPAN
      DEC1=((RTH-4.*Z)-SPANX)/SPAN
      DEC2=(.25E3-SPANX)/SPAN
      DEC3=(RTC+5.-SPANX)/SPAN
      COOLRT=RTC
      RTC=(RTC-SPANX)/SPAN
      RTCC=1.0-RTC
      ZZ=Z/SPAN
      SPANY=SPANX+.45969E3
      DE=DELAY/TIME
      RTS=(TBEGIN-SPANX)/SPAN
      IF((CUT.LT.0.001).AND.(DE.LT.0.001))THEN
       RTSS=0.
      ELSE
       RTSS=(1.0-RTS)/(CUT-DE)
      ENDIF
      MMM=0
135   CONS2=BIOTH*CONS1
      IND=0
      IC=IHEAT+1
      RT1=RTS
C
C     Initialize TEMP and FOTEST arrays
C
      DO 140 L=1,LC
      FOTEST(L)=0.0
140   TT(L)=TPI
C
C     Iterate for temperature versus time
C
      DO 600 J=1,ITERM
C
C     Correct RT for comup or cooling temp. changes
C
      IF(J.LT.DE)GO TO 600
      IF(J.GE.IC)GO TO 201
      IF(J.GT.CUT)GO TO 200
      RT=RTS+RTSS*(J-DE)
      GO TO 205
200   RT=1.0
      GO TO 205
C
C  Logarithmic cooling function (Uno and Hayakawa, 1980)
C
201   IF(((J-IHEAT)*TIME).LE.COMDN)THEN
       RT=1-(RTCC*(((J-IHEAT)*TIME)/COMDN)**COOLEX)
      ELSE
       RT=RTC
      ENDIF
      IF(J.EQ.IC)CONS2=BIOTC*CONS1
C
C     Calculate temperature profile
C
205   T(1)=TT(1)+CONS1*(TT(2)-TT(1))
      DO 210 I=2,LX
210   T(I)=TT(I)+CONS3*(TT(I-1)-2*TT(I)+TT(I+1))
      T(LC)=TT(LC)+CONS1*(TT(LX)-TT(LC))-CONS2*(TT(LC)-RT)
      IF((J.LT.IC).AND.(T(LC).GT.RT))T(LC)=RT
      DO 230 I=1,LC
       TT(I)=T(I)
230   CONTINUE
      RT1=RT
C
C  Calculate FOTEST using trapezoid rule
C
      DO 235 I=1,LC
       IF(T(I).GT.DEC1)THEN
        IF(T(I).LT.DEC2)THEN
         FOC(I)=TIME/10**((DEC2-T(I))/ZZ)
        ELSE
         FOC(I)=TIME*10**((T(I)-DEC2)/ZZ)
        ENDIF
        FOTEST(I)=FOTEST(I)+FOC(I)
       ENDIF
235   CONTINUE
      IF(FOT.LT.0.1)GO TO 253
C
C  The following code insures that the process time obtains the
C    correct Fo for the position in question.
C
      IF(((FOTEST(NN).GT.FOT).AND.(MMM.NE.2)).AND.
     C    (MMM.NE.3))THEN
       IHEAT=IHEAT-MIN
       MMM=1
      ELSE
       IF(MMM.EQ.0)GOTO253
       IF(((FOTEST(NN).LT.FOT).AND.(T(NN).LT.DEC1)).AND.
     C    ((J.GT.IHEAT).AND.(MMM.NE.3)))THEN
        MMM=2
        IHEAT=IHEAT+0.1*MIN
       ELSE
        IF((MMM.EQ.0).OR.(MMM.EQ.1))GOTO253
        IF((T(NN).GT.DEC1).OR.(J.LT.IHEAT))GOTO253
        MMM=3
        IF(((FOTEST(NN).GT.FOT).AND.(T(NN).LT.DEC1)).AND.
     C      (J.GT.IHEAT))THEN
         IF(TIME.GT.0.01)THEN
          IHEAT=IHEAT-1
         ELSE
          IHEAT=IHEAT-0.01*MIN
         ENDIF
        ELSE
         GOTO253
        ENDIF
       ENDIF
      ENDIF
      TIMC=IHEAT*TIME
      WRITE(6,240)TIMC
240   FORMAT(5X,'REITERATE WITH A HEATING TIME OF ',F7.3,' MIN')
      GO TO 135
253   IF(J/MIN*MIN.NE.J)GO TO 330
      DO 256 I=1,LC
256   TP(I)=T(I)*SPAN+SPANX
      PT=J*TIME
      RTR=RT*SPAN+SPANX
C
C  Set up RESULT array for output
C
      IND=IND+1
      RESULT(1,IND)=PT
      RESULT(2,IND)=RTR
      RESULT(3,IND)=FOTEST(NN)
      DO 300 I=LC,1,-1
       II=LC-(I-1)+3
       RESULT(II,IND)=TP(I)
300   CONTINUE
330   IF(J.LE.IC)GO TO 600
      IF(T(1).LT.DEC3)GO TO 605
600   CONTINUE
C
C   Find point at which cooling starts
C
605   DO 650 I=1,IND
       IF((RESULT(2,I).LT.RTH).AND.(RESULT(1,I).GT.COMUP))THEN
        CIND=I-1
        GOTO 660
       ENDIF
650   CONTINUE
C
C   Calculate time and temp arrays for FH and JH
C
660   DO 690 III=4,(LC+3)
       DO 665 I=CIND,1,-1
        II=I
        IF(RESULT(III,I).LT.(RTH-2.))GOTO 668
665    CONTINUE
668    DO 670 I=1,10
        TIMEFH(I)=RESULT(1,II)
        TEMPFH(I)=RESULT(III,II)
        II=II-1
670    CONTINUE
C
```

```
C  Calculate FH and JH
C
       CALL CALC(1,RTH,TI,TIMEFH,TEMPFH,COMUP,FH,JH,JC,FC)
       FHFC(III,1)=FH
       FHFC(III,2)=JH
C
C  Set up time and temp arrays for FC and JC calculation
C
       DO 672 I=IND,CIND,-1
        II=I
        IF(RESULT(III,I).GT.(COOLRT+5.))GOTO 675
672    CONTINUE
675    DO 680 I=1,10
        TIMEFC(I)=RESULT(1,II)-CIND
        TEMPFC(I)=RESULT(III,II)
        II=II-1
680    CONTINUE
C
C  Calculate FC and JC
C
       CALL CALC(2,COOLRT,RESULT(III,CIND),TIMEFC,TEMPFC,COMUP,FH,JH,
     C  JC,FC)
       FHFC(III,3)=FC
       FHFC(III,4)=JC
690   CONTINUE
C
C  Calculate Fo's for all positions using Simpson's rule.
C
      DO 697 I=4,LC+3
       FOSIMP=0.0
       DO 694 II=1,IND
        IF(RESULT(I,II).LT.(RTR-3.*Z))GOTO694
        TMID=(RESULT(I,II)+RESULT(I,II+1))/2.
        F=(0.5/3.)*(FOFUNC(RESULT(I,II),Z)+4.*FOFUNC(TMID,Z)+
     C    FOFUNC(RESULT(I,II+1),Z))
        FOSIMP=FOSIMP+F
694    CONTINUE
       FO(I)=FOSIMP
697   CONTINUE
C
C  Output
C
      WRITE(6,700)
700   FORMAT(///6X,'PROCESS  RETORT   TEST  SURFACE'/8X,'TIME',
     C  4X,'TEMP',5X,'FO',5X,'TEMP'/6X,
     C  '-------  ------  ------  ------')
      DO 720 I=1,IND
       WRITE(6,710)(RESULT(II,I),II=1,(LC+3))
710    FORMAT(8X,F5.1,3X,F5.1,2X,F6.3,1X,14(2X,F5.1))
720   CONTINUE
      WRITE(6,730)(FHFC(I,1),I=5,LC+3)
730   FORMAT(T29,'FH',7X,13(2X,F5.2))
```

```
      WRITE(6,740)(FHFC(I,2),I=5,LC+3)
740   FORMAT(T29,'JH',7X,13(2X,F5.3))
      WRITE(6,750)(FHFC(I,3),I=5,LC+3)
750   FORMAT(T29,'FC',7X,13(2X,F5.2))
      WRITE(6,760)(FHFC(I,4),I=5,LC+3)
760   FORMAT(T29,'JC',7X,13(2X,F5.3))
      WRITE(6,770)(FO(I),I=5,LC+3)
770   FORMAT(T19,'Simpson''s Fo',7X,13(2X,F5.2))
      WRITE(6,780)(FOTEST(I),I=LC-1,1,-1)
780   FORMAT(T19,'Trapezoid Fo',7X,13(1X,F6.3))
C
C  Set up output file for SAS
C
      POS=(NN-1)*AX/LX
      DELTAT=RTH-(TPI*SPAN+SPANX)
      IF(TIME.GT.0.01)THEN
       HTIME=TIMC+TIME/2.
      ELSE
       HTIME=TIMC+.005
      ENDIF
      WRITE(1,800)RUNNUM,HTIME,POS,AX,K,H,TBEGIN,COMUP,
     C   ALPHA,DELTAT
800   FORMAT(1X,I3,1X,F7.3,1X,F8.6,1X,F5.3,1X,F6.4,1X,
     C   F5.1,1X,F5.1,1X,F5.2,1X,F6.4,1X,F5.1)
610   CONTINUE
620   CONTINUE
      STOP
      END
C
C
      SUBROUTINE CALC(IND,RT,TI,TIME,TEMP,
     C   COMUP,FH,JH,JC,FC)
C
C  This subroutine calculates the heat penetration parameters Fh
C  and Jh, or Fc and Jc according to Stumbo (1973).  The straight
C  line portion of the heating or cooling curve is determined by
C  least squares linear regression of the plot of the log of the
C  temperature differential between the heating or cooling retort
C  temperatures and product temperatures versus time.
C
C  VARIABLES
C
C    COMUP      Time (min) for the retort to reach processing
C                 temperature
C    FC         Time (min) for the heating curve to transverse one
C                 log cycle
C    FH         Time (min) for the cooling curve to transverse one
C                 log cycle
C    IND        Indicates heating or cooling. 1=heating, 2=cooling
C    JC         Cooling lag factor
C    JH         Heating lag factor
C    RT         Heating or cooling retort temperature
```

```
C     TEMP( )    Array containing temperatures
C     TI         Initial product temperature at beginning of heating or
C                  cooling
C     TIME( )    Array containing times
C
C
       IMPLICIT REAL*8 (A-H,O-Z)
       DIMENSION TEMP(50),TIME(50)
       REAL JH,JC
       SX=0.
       SX2=0.
       SY=0.
       SXY=0.
       FH=0.
       JH=0.
       FC=0.
       JC=0.
       N=0
10     DO 30 I=1,10
20     IF(IND.EQ.1)Y=DLOG10(RT-TEMP(I))
       IF(IND.EQ.2)Y=DLOG10(TEMP(I)-RT)
       SX=SX+TIME(I)
       SX2=SX2+TIME(I)**2
       SY=SY+Y
       SY2=SY2+Y**2
       SXY=SXY+TIME(I)*Y
       N=N+1
30     CONTINUE
       B1=(SXY-SX*SY/N)/(SX2-(SX**2)/N)
       BO=(SY/N)-B1*SX/N
40     IF(IND.EQ.2)GOTO50
       FH=-1/B1
       JH=(10**(BO+B1*COMUP*0.6))/(RT-TI)
       GOTO60
50     JC=(10**BO)/(TI-RT)
       FC=-1.0/B1
60     RETURN
       END
C
C
C  Function to calculate Fo
C
       FUNCTION FOFUNC(TEMP,Z)
       IF(TEMP.GT.250.)THEN
        FOFUNC=10**((TEMP-250.)/Z)
       ELSE
        FOFUNC=1./10**((250.-TEMP)/Z)
       ENDIF
       RETURN
       END
```

APPENDIX G
FINITE DIFFERENCE PROGRAM TO SIMULATE A THERMAL PROCESS DETERMINATION; INFINITE BIOT NUMBER

```
C  This program simulates heat penetration into an infinite slab
C  for both heating and cooling processes with an infinite Biot
C  number.  The program uses the forward direction finite difference
C  method for an infinite slab geometry.  It will determine a
C  process time by iteration for a given F-value at any given node
C  in the infinite slab.  The process time predicted is accurate
C  to within 0.005 min. or to within half the time increment,
C  whichever is larger.  The F-value is determined in two ways:
C  at each time increment the F-value is integrated using the
C  Trapezoid rule, and the F-value is also determined by
C  integrating the data obtained every full minute by Simpson's
C  rule.  The F-value determined at every iteration is used for
C  process determination.
C
C  The program assumes a linear come up time from an initial retort
C  temperature after a specified delay to the processing temperature.
C  An exponential cool down profile is used.
C
C  The program terminates for a given set of input after the desired
C  process time has been found and either the center slab temperature
C  is within 5 F of the cooling retort temperature or the maximum
C  process time has been exceeded.
C
C  Heat penetration parameters, Fh, Jh, Fc, and Jc are calculated
C  for the heating and cooling curves found for each set of input
C  data.
C
C  VARIABLES
C
C     ALPHA=Thermal diffusivity of pouch contents (in**2/min)
C     AX=Total heat penetration distance (in)
C     CDT=Come down time (min)
C     CIND=Indicates zero cooling time and end of heating
C     COMDN=Time for retort to reach constant cooling temp. (min)
C     COMUP=Time for retort to reach constant heating temp. (min)
C     CONS1,CONS3=Dimensionless constants for heat penenetration
C     COOLEX=Exponent used to describe come down temperature profile
C     CUT=Come up time iteration number
C     DE=# of time increments before retort sees increase in
C          temperature at beginning of process
C     DEC1=Fract. temperature 4 Z-values from retort temperature
C     DEC2=Fract. temperature of 250 F
```

```
C     DEC3=Fract. temperature 5 F above cooling retort temperature
C     DELAY=Time (min) before retort sees increase in temperature at
C             beginning of process
C     DELX=Incremental distance across AX (in)
C     FHFC( , )=Array conaining FH, JH, FC, and JC values
C     FOC( )=Array containing incremental Fo at all positions
C               (min @ 250 F)
C     FOT=Fo desired for position NN; if FOT=0, program calculates
C                temps for the input heating time only
C     FOTEST( )=Array containing accumulated Fo at all positions
C                (min @ 250 F, integrated by trapezoid rule)
C     IC=# of iterations until cooling starts
C     IHEAT=# of iterations for heating cycle (includes CUT)
C     IND=Counter, number of minutes into the process
C     ITERM=Maximum # of iterations for heating and cooling
C     L=Array # distance increment (1=surface, LC=center)
C     LC=Array # for distance increment at center
C     LX=# of distance increments--must be even integer
C     MIN=# iterations per minute
C     NN=Position number (node) that process is designed for
C          (center=1)
C     PT=Current process time (min)
C     RESULT( , )=Array containing output
C     RT=Iteration retort temperature ( F)
C     RT1=Retort temp. for heating or cooling of previous
C           increment ( F)
C     RTC1=Retort temp. constants for cooling
C     RTS=Fract. temp. of initial retort temperature
C     RTSS=Fract. temp. constant for linear heating
C     SPAN=Difference between retort temperature and lowest exp.
C             temp. (F)
C     SPANX,SPANY=Constants for conv. between fract. and real temp.
C     T( )=Temperature array --fractional basis
C     TBEGIN=Retort temperature at zero process time (after DELAY)
C     TEMPFC( )=Temperature array for FC calculations
C     TEMPFH( )=Temperature array for FH calculations
C     TIMC=Time to cooling (min)
C     TIMTOT=Maximum process time (min)
C     TIME=Time increment--must be integer divisor of 1 min (min)
C     TIMEFC( )=Time array for FC calculations
C     TIMEFH( )=Time array for FH calculations
C     TT( )=Previous temperature array--fractional basis
C     TP( )=Temperature array--real basis (F)
C     TPI=Intial temp. of pouch contents ( F)
C     TT( )=Previous temperature array--fractional basis
C     Z=Z value for Fo calculations ( F)
C     ZZ=Lethality conv. factor
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION T(25),TP(25),TT(25),RESULT(25,300),FO(25),
     C  TIMEFH(10),TIMEFC(10),TEMPFH(10),TEMPFC(10),FHFC(25,4),
     C  FOC(25),FOTEST(25)
```

```
      INTEGER CIND,RUNNUM
      REAL*8 JH,JC,K
      OPEN(UNIT=5,FILE='SLABNOBI.DAT',STATUS='OLD',
     C  RECORDTYPE='VARIABLE')
      OPEN(UNIT=6,FILE='SLABNOBI.RES',STATUS='NEW')
      OPEN(UNIT=1,FILE='SLABNOBI.SAS',STATUS='NEW')
      DO 610 JJ=1,500
      READ(5,*,END=620)RUNNUM,LX,AX,TIME,TIMC,TIMTOT
      READ(5,*)RTH,RTC,TPI,COMUP,ALPHA
      READ(5,*)DELAY,TBEGIN,COMDN,COOLEX
      READ(5,*)Z,FOT,NN
      IHEAT=TIMC/TIME
      ITERM=TIMTOT/TIME
      WRITE(6,130)RUNNUM,AX,LX,TIME,TIMC
130   FORMAT('1',4X,'RUN NUMBER',I4/5X,'--------------'//
     C4X,'INFINITE BIOT NUMBER'//5X,
     C'SLAB HALF THICKNESS = ',F5.3,' IN. DIVIDED INTO ',
     CI2,' INCREMENTS',/,5X,'TIME INTERVAL = ',F5.3,' MIN.',
     C'     HEATING TIME = ',F6.2,' MIN.')
      WRITE(6,131)RTH,RTC,TPI,COMUP,ALPHA
131   FORMAT(5X,
     C'RETORT(HEATING)= ',F5.1,'F',/,5X,'RETORT(COOLING)=',F5.1,
     C'F    POUCH(INITIAL)=',F5.1,'F',/,5X,'COMEUP TIME = ',F5.2,
     C' MIN',/,5X,'THERMAL DIFUSIVITY = ',
     CE10.4,' IN2/MIN')
      WRITE(6,129)DELAY,TBEGIN,COMDN,COOLEX
129   FORMAT(5X,'DELAY BEFORE POUCHES SEE RETORT ',
     C  'TEMPERATURE INCREASE = ',F5.2,' MIN'/5X,
     C  'RETORT TEMP POUCHES EXPOSED TO IMMEDIATELY AFTER DELAY'
     C  ' = ',F5.1,'F'/5X,'COOL DOWN TIME = ',F4.1,' MIN'/5X,
     C  'EXPONENT USED IN CALCULATING COOL DOWN PROFILE = ',
     C  F5.3)
      DELX=AX/LX
      CONS1=2*ALPHA*TIME/DELX**2
      CONS3=CONS1/2
      WRITE(6,132)Z,NN
132   FORMAT(5X,'Z VALUE = ',F5.1,5X,'TEST Fo NODE = ',
     C  I2,'  (CENTER=1)'//5X)
      IF(CONS3.LT.0.5)GO TO 134
      WRITE(6,133)
133   FORMAT(//5X,'STABILITY CRITERIA NOT MET')
      GO TO 610
134   MIN=1/TIME
      LC=LX+1
      CUT=COMUP/TIME
      IF(TPI.LT.RTC)SPANX=TPI
      IF(RTC.LE.TPI)SPANX=RTC
      SPAN=RTH-SPANX
      TI=TPI
      TPI=(TPI-SPANX)/SPAN
      DEC1=((RTH-4.*Z)-SPANX)/SPAN
      DEC2=(.25E3-SPANX)/SPAN
      DEC3=(RTC+5.-SPANX)/SPAN
      COOLRT=RTC
      RTC=(RTC-SPANX)/SPAN
      RTCC=1.0-RTC
      ZZ=Z/SPAN
      SPANY=SPANX+.45969E3
      DE=DELAY/TIME
      RTS=(TBEGIN-SPANX)/SPAN
      IF((CUT.LT.0.001).AND.(DE.LT.0.001))THEN
       RTSS=0.
      ELSE
       RTSS=(1.0-RTS)/(CUT-DE)
      ENDIF
      MMM=0
135   IND=0
      IC=IHEAT+1
      RT1=RTS
C
C     Initialize TEMP and FOTEST arrays
C
      DO 140 L=1,LC
      FOTEST(L)=0.0
140   TT(L)=TPI
C
C     Iterate for temperature versus time
C
      DO 600 J=1,ITERM
C
C     Correct RT for comup or cooling temp. changes
C
      IF(J.LT.DE)GO TO 600
      IF(J.GE.IC)GO TO 201
      IF(J.GT.CUT)GO TO 200
      RT=RTS+RTSS*(J-DE)
      GO TO 205
200   RT=1.0
      GO TO 205
C
C  Logarithmic cooling function (Uno and Hayakawa, 1980)
C
201   IF(((J-IHEAT)*TIME).LE.COMDN)THEN
       RT=1-(RTCC*(((J-IHEAT)*TIME)/COMDN)**COOLEX)
      ELSE
       RT=RTC
      ENDIF
C
C     Calculate temperature profile
C
205   T(1)=TT(1)+CONS1*(TT(2)-TT(1))
      DO 210 I=2,LX
210   T(I)=TT(I)+CONS3*(TT(I-1)-2*TT(I)+TT(I+1))
      T(LC)=RT
      DO 230 I=1,LC
       TT(I)=T(I)
230   CONTINUE
      RT1=RT
C
C  Calculate FOTEST using trapezoid rule
C
      DO 235 I=1,LC
       IF(T(I).GT.DEC1)THEN
        IF(T(I).LT.DEC2)THEN
         FOC(I)=TIME/10**((DEC2-T(I))/ZZ)
        ELSE
         FOC(I)=TIME*10**((T(I)-DEC2)/ZZ)
        ENDIF
        FOTEST(I)=FOTEST(I)+FOC(I)
       ENDIF
235   CONTINUE
      IF(FOT.LT.0.1)GO TO 253
C
C  The following code insures that the process time obtains the
C    correct Fo for the position in question.
C
      IF(((FOTEST(NN).GT.FOT).AND.(MMM.NE.2)).AND.
     C    (MMM.NE.3))THEN
       IHEAT=IHEAT-MIN
       MMM=1
      ELSE
       IF(MMM.EQ.0)GOTO253
       IF(((FOTEST(NN).LT.FOT).AND.(T(NN).LT.DEC1)).AND.
     C    ((J.GT.IHEAT).AND.(MMM.NE.3)))THEN
        MMM=2
        IHEAT=IHEAT+0.1*MIN
       ELSE
        IF((MMM.EQ.0).OR.(MMM.EQ.1))GOTO253
        IF((T(NN).GT.DEC1).OR.(J.LT.IHEAT))GOTO253
        MMM=3
        IF(((FOTEST(NN).GT.FOT).AND.(T(NN).LT.DEC1)).AND.
     C      (J.GT.IHEAT))THEN
         IF(TIME.GT.0.01)THEN
          IHEAT=IHEAT-1
         ELSE
          IHEAT=IHEAT-0.01*MIN
         ENDIF
        ELSE
         GOTO253
        ENDIF
       ENDIF
      ENDIF
      TIMC=IHEAT*TIME
      WRITE(6,240)TIMC
240   FORMAT(5X,'REITERATE WITH A HEATING TIME OF ',F7.3,' MIN')
      GO TO 135
```

```
253   IF(J/MIN*MIN.NE.J)GO TO 330
C
C  Set up RESULT array for output
C
      DO 256 I=1,LC
256   TP(I)=T(I)*SPAN+SPANX
      PT=J*TIME
      RTR=RT*SPAN+SPANX
      IND=IND+1
      RESULT(1,IND)=PT
      RESULT(2,IND)=RTR
      RESULT(3,IND)=FOTEST(NN)
      DO 300 I=LC,1,-1
       II=LC-(I-1)+3
       RESULT(II,IND)=TP(I)
300   CONTINUE
330   IF(J.LE.IC)GO TO 600
      IF(T(1).LT.DEC3)GO TO 605
600   CONTINUE
C
C   Find point at which cooling starts
C
605   DO 650 I=1,IND
       IF((RESULT(2,I).LT.RTH).AND.(RESULT(1,I).GT.COMUP))THEN
        CIND=I-1
        GOTO 660
       ENDIF
650   CONTINUE
C
C   Calculate time and temp arrays for FH and JH
C
660   DO 690 III=5,(LC+3)
       DO 665 I=CIND,1,-1
        II=I
        IF(RESULT(III,I).LT.(RTH-2.))GOTO 668
665    CONTINUE
668    DO 670 I=1,10
        TIMEFH(I)=RESULT(1,II)
        TEMPFH(I)=RESULT(III,II)
        II=II-1
670    CONTINUE
C
C  Calculate FH and JH
C
       CALL CALC(1,RTH,TI,TIMEFH,TEMPFH,COMUP,FH,JH,JC,FC)
       FHFC(III,1)=FH
       FHFC(III,2)=JH
C
C  Set up time and temp arrays for FC and JC calculation
C
       DO 672 I=IND,CIND,-1
        II=I
        IF(RESULT(III,I).GT.(COOLRT+5.))GOTO 675
672    CONTINUE
675    DO 680 I=1,10
        TIMEFC(I)=RESULT(1,II)-CIND
        TEMPFC(I)=RESULT(III,II)
        II=II-1
680    CONTINUE
C
C  Calculate FC and JC
C
       CALL CALC(2,COOLRT,RESULT(III,CIND),TIMEFC,TEMPFC,COMUP,FH,JH,
     C  JC,FC)
       FHFC(III,3)=FC
       FHFC(III,4)=JC
690   CONTINUE
C
C  Calculate Fo's for all positions using Simpson's rule.
C
      DO 697 I=4,LC+3
       FOSIMP=0.0
       DO 694 II=1,IND
        IF(RESULT(I,II).LT.(RTR-3.*Z))GOTO694
        TMID=(RESULT(I,II)+RESULT(I,II+1))/2.
        F=(0.5/3.)*(FOFUNC(RESULT(I,II),Z)+4.*FOFUNC(TMID,Z)+
     C    FOFUNC(RESULT(I,II+1),Z))
        FOSIMP=FOSIMP+F
694    CONTINUE
       FO(I)=FOSIMP
697   CONTINUE
C
C  Output
C
      WRITE(6,700)
700   FORMAT(///6X,'PROCESS  RETORT   TEST  SURFACE'/8X,'TIME',
     C  4X,'TEMP',5X,'FO',5X,'TEMP'/6X,
     C  '-------  ------  ------  ------')
      DO 720 I=1,IND
       WRITE(6,710)(RESULT(II,I),II=1,(LC+3))
710    FORMAT(8X,F5.1,3X,F5.1,2X,F6.3,1X,14(2X,F5.1))
720   CONTINUE
      WRITE(6,730)(FHFC(I,1),I=5,LC+3)
730   FORMAT(T29,'FH',7X,13(2X,F5.2))
      WRITE(6,740)(FHFC(I,2),I=5,LC+3)
740   FORMAT(T29,'JH',7X,13(2X,F5.3))
      WRITE(6,750)(FHFC(I,3),I=5,LC+3)
750   FORMAT(T29,'FC',7X,13(2X,F5.2))
      WRITE(6,760)(FHFC(I,4),I=5,LC+3)
760   FORMAT(T29,'JC',7X,13(2X,F5.3))
      WRITE(6,770)(FO(I),I=5,LC+3)
770   FORMAT(T19,'Simpson''s Fo',7X,13(2X,F5.2))
      WRITE(6,780)(FOTEST(I),I=LC-1,1,-1)
780   FORMAT(T19,'Trapezoid Fo',7X,13(1X,F6.3))
```

```
C
C  Set up output file for SAS
C
      POS=(NN-1)*AX/LX
      DELTAT=RTH-(TPI*SPAN+SPANX)
      IF(TIME.GT.0.01)THEN
       HTIME=TIMC+TIME/2.
      ELSE
       HTIME=TIMC+.005
      ENDIF
      WRITE(1,800)RUNNUM,Z,HTIME,POS,AX,TBEGIN,COMUP,
     C   ALPHA,DELTAT
800   FORMAT(1X,I3,1X,F4.1,1X,F7.3,1X,F8.6,1X,F5.3,
     C   1X,F5.1,1X,F5.2,1X,F6.4,1X,F5.1)
610   CONTINUE
620   CONTINUE
      STOP
      END
C
C
      SUBROUTINE CALC(IND,RT,TI,TIME,TEMP,
     C   COMUP,FH,JH,JC,FC)
C
C  This subroutine calculates the heat penetration parameters Fh
C  and Jh, or Fc and Jc according to Stumbo (1973).  The straight
C  line portion of the heating or cooling curve is determined by
C  least squares linear regression of the plot of the log of the
C  temperature differential between the heating or cooling retort
C  temperatures and product temperatures versus time.
C
C  VARIABLES
C
C    COMUP     Time (min) for the retort to reach processing
C                temperature
C    FC        Time (min) for the heating curve to transverse one
C                log cycle
C    FH        Time (min) for the cooling curve to transverse one
C                log cycle
C    IND       Indicates heating or cooling. 1=heating, 2=cooling
C    JC        Cooling lag factor
C    JH      . Heating lag factor
C    RT        Heating or cooling retort temperature
C    TEMP( )   Array containing temperatures
C    TI        Initial product temperature at beginning of heating or
C                cooling
C    TIME( )   Array containing times
C
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION TEMP(50),TIME(50)
      REAL JH,JC
      SX=0.
      SX2=0.
      SY=0.
      SXY=0.
      FH=0.
      JH=0.
      FC=0.
      JC=0.
      N=0
10    DO 30 I=1,10
20    IF(IND.EQ.1)Y=DLOG10(RT-TEMP(I))
      IF(IND.EQ.2)Y=DLOG10(TEMP(I)-RT)
      SX=SX+TIME(I)
      SX2=SX2+TIME(I)**2
      SY=SY+Y
      SY2=SY2+Y**2
      SXY=SXY+TIME(I)*Y
      N=N+1
30    CONTINUE
      B1=(SXY-SX*SY/N)/(SX2-(SX**2)/N)
      B0=(SY/N)-B1*SX/N
40    IF(IND.EQ.2)GOTO50
      FH=-1/B1
      JH=(10**(B0+B1*COMUP*0.6))/(RT-TI)
      GOTO60
50    JC=(10**B0)/(TI-RT)
      FC=-1.0/B1
60    RETURN
      END
C
C
C  Function to calculate Fo
C
      FUNCTION FOFUNC(TEMP,Z)
      IF(TEMP.GT.250.)THEN
       FOFUNC=10**((TEMP-250.)/Z)
      ELSE
       FOFUNC=1./10**((250.-TEMP)/Z)
      ENDIF
      RETURN
      END
```

APPENDIX H
PROGRAM FOR INFINITE SLAB EXACT SOLUTION, FINITE BIOT NUMBER

```
C  This program calculates the exact solution for an
C  infinite slab with equal h-values on both surfaces of the
C  slab.  The formulas used in tis program were taken from
C  Ball and Olson (1957) pp.218-221, however the formulas can
C  be found in any number of heat transfer books.
C
C  The program calculates temperatures at different times
C  for a number of equally spaced positions in the slab (specified
C  by DIV).  Any number of different sets of input may be analyzed
C  in one execution of the program.
C
C  VARIABLES
C
C   A            1/2 slab thickness (in.)
C   ALPHA        Thermal diffusivity (in**2/min)
C   DIV          Number of divisions 1/2 slab thickness is to be
C                   divided into.
C   FH( )        Array containing Fh values for different positions.
C   H            h-value (BTU/hr ft**2 F)
C   II           Counter for time; for TIMST, II=2
C   JJ           Counter for position; for X=0 (center), JJ=2
C   JH( )        Array containing JH values for different positions.
C   K            Thermal conductivity (BTU/hr ft F)
C   Q,R,S        Variables used in finding roots of transcendental
C                   equation.
C   ROOT( )      Array containing roots of the transcendental equation.
C   RT           Retort temp
C   TIMST        Time at which calculations are started. (min)
C   TIMINC       Time increment. (min)
C   TIMTOT       Total process time. (min)
C   TIME         Current time. (min)
C   TI           Initial food temp
C   T            Temp calculated after each iteration in infinite
C                   series.
C   TPREV        Temp calculated from previous iteration in infinite
C                   series.
C   TEMP( , )    Array containing position, temps, and time
C                   Times in TEMP(1,)
C                   Position in TEMP(,1)
C                   Temps in appropriate location
C   TEMPFH( )    Array containing temps for FH and JH calculation.
C   TIMEFH( )    Array containing times for FH and JH calculation.
C   X            Position in slab (center = 0.0)
```

```
C
C
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 K,JH(20),JJH,JC
      DIMENSION TEMP(20,70),FH(20),TIMEFH(20),TEMPFH(20),ROOT(50)
      OPEN(UNIT=5,FILE='EXTSLBH.DAT',STATUS='OLD',
     C   RECORDTYPE='VARIABLE')
      OPEN(UNIT=6,FILE='EXTSLBH.RES',STATUS='NEW')
10    READ(5,*,END=1000)A,DIV,RT,TI
      READ(5,*)H,K,ALPHA
      READ(5,*)TIMST,TIMINC,TIMTOT
      PI=3.14159265359
C
C  Change H and K for consistant units
C
      H=H/(144.*60.)
      K=K/(12.*60.)
C
C  Calculation of the first 50 roots of the transcendental
C    equation using bisection.  The roots are stored
C    in the ROOT( ) array.
C
C  Calculate the number of iterations needed to give an
C    error < 0.0000001 for a segment of 2*PI.  (Add 2 iterations
C    for safety.)
C
      G=2.
      NUM=(DLOG10(PI/(A*0.0000001))/DLOG10(G))+1.
      DO 35 J=1,50
C
C       Calculate the first two seeds for the Jth root and make sure
C         they are opposite signs.
C
       Q=(2.*J-1.)*PI/(2.*A)+3.13/(2.*A)
       QRES=1./DTAN(Q*A)-K*Q/H
       R=(2.*J-1.)*PI/(2.*A)-3.13/(2.*A)
       RRES=1./DTAN(R*A)-K*R/H
       IF(((QRES.LT.0.).AND.(RRES.LT.0.)).OR.
     C   ((QRES.GT.0.).AND.(RRES.GT.0.)))THEN
        WRITE(6,20)J,QRES,RRES
20      FORMAT(1X,'THE ',I2,' SEED HAD THE SAME SIGN.',/1X,'Q = ',
     C     E14.6/1X,'R = ',E14.6)
        GOTO1000
       ELSE
        DO 30 I=1,NUM
         S=(Q+R)/2.
         SRES=1./DTAN(S*A)-K*S/H
         IF(SRES.LT.0.)THEN
          IF(QRES.GE.0.)THEN
           RRES=SRES
           R=S
          ENDIF
          IF(RRES.GE.0.)THEN
           QRES=SRES
           Q=S
          ENDIF
         ELSE
          IF(QRES.LE.0.)THEN
           RRES=SRES
           R=S
          ENDIF
          IF(RRES.LE.0.)THEN
           QRES=SRES
           Q=S
          ENDIF
         ENDIF
30      CONTINUE
       ENDIF
       ROOT(J)=(Q+R)/2.
35    CONTINUE
      JJ=2
      X=0.
40    TEMP(JJ,1)=X
      II=2
      TIME=TIMST
50    TEMP(1,II)=TIME
C
C       The following DO-loop calculates the temperature at a
C  specific position for a specific time.  The infinite series
C  is terminated after 50 terms or if the relative change in
C  temperature changes by less than 0.00001 from one term to
C  the next.
C
      SUM=0.0
      DO 70 N=1,50
       SUM=SUM+(EXP(-(ROOT(N)**2)*ALPHA*TIME)*(DSIN(ROOT(N)
     C     *A)*DCOS(ROOT(N)*X))/((ROOT(N)*A)+DSIN(ROOT(N)*A)*
     C     DCOS(ROOT(N)*A)))
       T=RT-2.*SUM*(RT-TI)
       IF(N.EQ.1)GOTO60
       IF(ABS((T-TPREV)/T).LT.0.00001)GOTO80
60     TPREV=T
70    CONTINUE
80    TEMP(JJ,II)=T
C
C       Check to see if the time elapsed is greater than TIMTOT.
C  If not, return and calculate temperature for the next time
C  period.  If so, go on to calculate temperatures for a new
C  position.
C
      IF(TIME.GE.TIMTOT)GOTO90
      TIME=TIME+TIMINC
      II=II+1
      GOTO50
```

```
90    X=(JJ-1)*A/DIV
C
C        Check to see if the new position X is still within the
C     slab.  If so, return and calculate temperatures for the new
C     position.  If not, calculate FH, JH, and WRITE output.
C
      IF(X.GE.A)GOTO100
      JJ=JJ+1
      GOTO40
C
C     Set up arrays and calculate FH & JH using CALC subroutine.
C
100   IF((II.LT.11).OR.((RT-TI).LT.0.0))THEN
       DO 110 I=1,20
        JH(I)=0.0
        FH(I)=0.0
110    CONTINUE
      ELSE
       DO 120 I=II,2,-1
        TIMEFH(II-I+1)=TEMP(1,I)
        IF((II-I+1).EQ.20)GOTO125
120    CONTINUE
125    DO 140 I=2,JJ
        DO 130 J=II,2,-1
         TEMPFH(II-J+1)=TEMP(I,J)
         IF((II-J+1).EQ.20)GOTO135
130     CONTINUE
135     CALL CALC(1,RT,TI,TIMEFH,TEMPFH,0.0,F,JJH,FC,JC)
        FH(I)=F
        JH(I)=JJH
140    CONTINUE
      ENDIF
C
C     Return H and K to original units for output.
C
      H=H*144.*60.
      K=K*12.*60.
      WRITE(6,590)
590   FORMAT('1','EXACT SOLUTION RESULTS'/1X,
     C '----------------------')
      WRITE(6,600)A,ALPHA,K,H,RT,TI,TIMTOT
600   FORMAT(1X,'SLAB HALF THICKNESS = ',F5.3,' IN'/1X,
     C 'ALPHA = ',F6.4,' IN**2/MIN'/1X,'K = ',F6.4,1X,
     C 'BTU/HR FT F'/1X,'H = ',F9.1,'  BTU/HR FT**2 F'/
     C 1X,'RETORT TEMP  = ',F5.1/1X,'INITIAL TEMP = ',
     C F5.1/1X,'TIMTOT = ',F5.1)
      WRITE(6,610)(TEMP(I,1),I=3,JJ)
610   FORMAT('0',5X,'TIME',4X,'CENTER'/5X,'(MIN.)',4X,
     C 'X=0.0',13(2X,F6.4))
      WRITE(6,615)
615   FORMAT(' ')
      DO 630 I=2,II
```

```
       WRITE(6,620)(TEMP(J,I),J=1,JJ)
620    FORMAT(5X,F5.1,2X,14(3X,F5.1))
630   CONTINUE
      WRITE(6,640)(FH(I),I=2,JJ)
640   FORMAT(11X,'FH',2X,14(F5.2,3X))
      WRITE(6,650)(JH(I),I=2,JJ)
650   FORMAT(11X,'JH',2X,14(F5.3,3X))
      GOTO10
1000  STOP
      END
C
C
C
      SUBROUTINE CALC(IND,RT,TI,TIME,TEMP,
     C   COMUP,FH,JH,JC,FC)
C
C  This subroutine calculates the heat penetration parameters Fh
C  and Jh, or Fc and Jc according to Stumbo (1973).  The straight
C  line portion of the heating or cooling curve is determined by
C  least squares linear regression of the plot of the log of the
C  temperature differential between the heating or cooling retort
C  temperatures and product temperatures versus time.
C
C  VARIABLES
C
C    COMUP      Time (min) for the retort to reach processing
C                 temperature
C    FC         Time (min) for the heating curve to transverse one
C                 log cycle
C    FH         Time (min) for the cooling curve to transverse one
C                 log cycle
C    IND        Indicates heating or cooling. 1=heating, 2=cooling
C    JC         Cooling lag factor
C    JH         Heating lag factor
C    RT         Heating or cooling retort temperature
C    TEMP( )    Array containing temperatures
C    TI         Initial product temperature at beginning of heating or
C                 cooling
C    TIME( )    Array containing times
C
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION TEMP(20),TIME(20)
      REAL JH,JC
      SX=0.
      SX2=0.
      SY=0.
      SXY=0.
      FH=0.
      JH=0.
      FC=0.
      JC=0.
      N=0
10    DO 30 I=1,10
20    IF(IND.EQ.1)Y=DLOG10(RT-TEMP(I))
      IF(IND.EQ.2)Y=DLOG10(TEMP(I)-RT)
      SX=SX+TIME(I)
      SX2=SX2+TIME(I)**2
      SY=SY+Y
      SY2=SY2+Y**2
      SXY=SXY+TIME(I)*Y
      N=N+1
30    CONTINUE
      B1=(SXY-SX*SY/N)/(SX2-(SX**2)/N)
      B0=(SY/N)-B1*SX/N
40    IF(IND.EQ.2)GOTO50
      FH=-1/B1
      JH=(10**(B0+B1*COMUP*0.6))/(RT-TI)
      GOTO60
50    JC=(10**B0)/(TI-RT)
      FC=-1.0/B1
60    RETURN
      END
```

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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